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Attorneys for Plaintiff
NAZOMI COMMUNICATIONS, INC.

UNITED STATES DISTRICT COURT

CENTRAL DISTRICT OF CALIFORNIA

Nazomi Communications, Inc.,

Plaintiff,

v.

Samsung Telecommunications, Inc., Samsung Electronics Co., Ltd., Samsung Electronics America, Inc., HTC Corp., HTC America, Inc., LG Electronics, Inc., LG Electronics U.S.A., Inc., Kyocera Corporation, Kyocera International, Inc., Kyocera Communications Inc., and Kyocera America, Inc.

Defendants.

SA10-CV-01527 AG (RNBx)

COMPLAINT FOR PATENT INFRINGEMENT

JURY TRIAL DEMANDED

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Plaintiff Nazomi Communications, Inc. ("Nazomi"), by and through its undersigned counsel, complains as follows:

JURISDICTION AND VENUE

1. This infringement action arises under the patent laws of the United States, Title 35 of the United States Code, including but not limited to 35 U.S.C. § 271.

2. This Court has subject matter jurisdiction pursuant to 28 U.S.C. §§ 1331 and 1338(a).

3. Venue is proper in this judicial district pursuant to 28 U.S.C. §§ 1391(b), 1391(c), and 1400(b).

THE PARTIES

4. Plaintiff Nazomi Communications, Inc. is a corporation organized and existing under the laws of the State of Delaware with its principal place of business at 3561 Homestead Road, Suite 571, Santa Clara, California 95051.

5. On information and belief, Defendant LG Electronics, Inc. is a foreign corporation organized and existing under the laws of Korea, with its principal place of business at LG Twin Towers, 20, Yeouido-dong, Yeongdeungpo-gu, Seoul 150-721, South Korea. On information and belief, Defendant LG Electronics U.S.A., Inc. is a corporation organized and existing under the laws of the State of Delaware, with its principal place of business located at 1000 Sylvan Avenue, Englewood Cliffs, NJ 07632. LG Electronics, Inc. and LG Electronics U.S.A., Inc. are referred to collectively herein as "LG."

6. On information and belief, Defendant Samsung Electronics Co., Ltd. is a foreign corporation organized and existing under the laws of Korea, with its principal place of business located at 250, 2-ga, Taepyong-ro, Jung-gu, Seoul 100-742, Korea. On information and belief, Defendant Samsung Electronics America, Inc., is a corporation organized and existing under the laws of the State of New York, with its principal place of business located at 105 Challenger Road,

Ridgefield Park, NJ 07660. On information and belief, Samsung Telecommunications America, LLC is a corporation organized and existing under the laws of the State of Delaware, with its principal place of business located at 1301 Lookout Dr., Richardson, TX 75082. Samsung Electronics Co., Ltd., Samsung Electronics America, Inc. and Samsung Telecommunications America, LLC are referred to collectively herein as "Samsung."

7. On information and belief, HTC Corp. is a foreign corporation organized and existing under the laws of Taiwan, with its principal place of business at 23 Hsin Hua Rd., Taoyuan, 330, Taiwan. On information and belief, HTC America, Inc. is a corporation organized and existing under the laws of the State of Texas, with its principle place of business located at 13920 S.E. Eastgate Way, Suite 400, Bellevue, WA 98005. HTC Corp. and HTC America, Inc. are referred to collectively herein as "HTC."

8. On information and belief, Defendant Kyocera Corporation is a foreign corporation organized and existing under the laws of Japan, with its principal place of business located at 6 Takeda Tobadono-cho, Fushimi-ku, Kyoto, 612-8501, Japan. On information and belief, Defendant Kyocera International, Inc. is a corporation organized and existing under the laws of the State of California, with its principal place of business located at 8611 Balboa Ave., San Diego, CA 92123. On information and belief, Kyocera Communications, Inc. is a corporation organized and existing under the laws of the State of Delaware, with its principal place of business located at 10300 Campus Point Dr., San Diego, CA 92121. On information and belief, Kyocera America, Inc. is a corporation organized and existing under the laws of the State of California, with its principal place of business located at 8611 Balboa Ave., San Diego, CA 92123. Kyocera Corporation, Kyocera International, Inc., Kyocera Communications, Inc., and Kyocera America, Inc. are referred to collectively herein as "Kyocera."

BACKGROUND

9. Nazomi Communications, Inc. was founded in September 1998 by three Java technology and embedded systems veterans for the purpose of enhancing the performance of applications that run on the Java platform and other universal runtime platforms. Nazomi's pioneering technologies included the JSTAR Java Coprocessor technology and the JA108 Java and Multimedia Application Processor, which were targeted at wireless mobile devices, internet appliances, and embedded systems. Nazomi's technology and products were adopted by leading phone manufacturers and incorporated into millions of smart phones. In the years since Nazomi's introduction of the JSTAR and JA108 products, Java hardware and software acceleration has been widely adopted for wireless mobile and embedded systems applications. Java is now used as a platform on hundreds of millions of devices.

10. On July 18, 2006, the United States Patent and Trademark Office duly and legally issued United States Patent No. 7,080,362 entitled "Java Virtual Machine Hardware for RISC and CISC Processors" ("the '362 patent"). A true and correct copy of the '362 patent is attached as Exhibit 1.

11. On May 29, 2007, the United States Patent and Trademark Office duly and legally issued United States Patent No. 7,225,436 entitled "Java Hardware Accelerator Using Microcode Engine" ("the '436 patent"). A true and correct copy of the '436 patent is attached as Exhibit 2.

12. On January 8, 2002, the United States Patent and Trademark Office duly and legally issued United States Patent No. 6,338,160 entitled "Constant Pool Reference Resolution Method" ("the '160 patent"). A true and correct copy of the '160 patent is attached as Exhibit 3.

13. Nazomi is the owner and possessor of all rights, title, and interest in the '362, '436, and '160 patents.

14. Defendant Samsung makes, uses, sells, and/or offers for sale within the

United States and this judicial district consumer electronic devices containing processor cores capable of Java hardware acceleration including, but not limited to, the Instinct s30 (SPH-M810) mobile phone. Upon information and belief, the Instinct s30 (SPH-M810) mobile phone incorporates an ARM926EJ-S processor core capable of Java hardware acceleration.

15. Defendants Samsung Telecommunications, Inc., Samsung Electronics Co., Ltd., and Samsung Electronics America, Inc. make, use, sell, and/or offer for sale within the United States and this judicial district consumer electronic devices that use a virtual machine ("VM") to resolve constant pool references including, but not limited to, the Captivate (SGH-I897) mobile phone. Upon information and belief, the Captivate (SGH-I897) mobile phone uses a VM to resolve constant pool references.

16. Defendant HTC makes, uses, sells, and/or offers for sale within the United States and this judicial district consumer electronic devices that use a VM to resolve constant pool references including, but not limited to, the Droid Incredible mobile phone. Upon information and belief, the Droid Incredible mobile phone uses a VM to resolve constant pool references.

17. Defendant LG makes, uses, sells, and/or offers for sale within the United States and this judicial district consumer electronic devices containing processor cores capable of Java hardware acceleration including, but not limited to, the LX370 mobile phone. Upon information and belief, the LX370 mobile phone incorporates an ARM926EJ-S processor core capable of Java hardware acceleration.

18. Defendant LG likewise makes, uses, sells, and/or offers for sale within the United States and this judicial district consumer electronic devices that use a VM to resolve constant pool references including, but not limited to, the Ally (VS740) mobile phone. Upon information and belief, the Ally (VS740) mobile phone uses a VM to resolve constant pool references.

19. Defendant Kyocera makes, uses, sells, and/or offers for sale within the United States and this judicial district consumer electronic devices containing processor cores capable of Java hardware acceleration including, but not limited to, the PRO-700 mobile phone. Upon information and belief, the PRO-700 mobile phone incorporates an ARM926EJ-S processor core capable of Java hardware acceleration.

20. Defendant Kyocera likewise makes, uses, sells, and/or offers for sale within the United States and this judicial district consumer electronic devices that use a VM to resolve constant pool references including, but not limited to, the Zio (M6000) mobile phone. Upon information and belief, the Zio (M6000) mobile phone uses a VM to resolve constant pool references.

COUNT I

INFRINGEMENT OF THE '362 PATENT

21. Plaintiff incorporates each of the preceding paragraphs 1-20 as if fully set forth herein.

22. Defendants Samsung, LG, and Kyocera have been and are directly infringing the '362 patent by making, using, selling, and/or offering for sale within the United States and this judicial district the products identified in paragraphs 14-20.

23. The infringement by Defendants of the '362 patent has injured Plaintiff and will cause irreparable injury and damage in the future unless Defendants are enjoined from infringing the '362 patent.

COUNT II

INFRINGEMENT OF THE '436 PATENT

24. Plaintiff incorporates each of the preceding paragraphs 1-23 as if fully set forth herein.

25. Defendants Samsung, LG, and Kyocera have been and are directly infringing the '436 patent by making, using, selling, and/or offering for sale within

the United States and this judicial district the products identified in paragraphs 14-20.

26. The infringement by Defendants of the '436 patent has injured Plaintiff and will cause irreparable injury and damage in the future unless Defendants are enjoined from infringing the '436 patent.

COUNT III

INFRINGEMENT OF THE '160 PATENT

27. Plaintiff incorporates each of the preceding paragraphs 1-26 as if fully set forth herein.

28. Defendants Samsung, HTC, LG, and Kyocera have been and are directly infringing the '160 patent by making, using, selling, and/or offering for sale within the United States and this judicial district the products identified in paragraphs 14-20.

29. The infringement by Defendants of the '160 patent has injured Plaintiff and will cause irreparable injury and damage in the future unless Defendants are enjoined from infringing the '160 patent.

PRAYER FOR RELIEF

WHEREFORE, Nazomi prays for judgment against all Defendants as follows:

a) That the Court find that Defendants have each infringed and are each presently infringing, United States Patent Nos. 7,080,362, 7,225,436, and 6,338,160;

b) That the Court find the '362, '436, '160 patents valid and enforceable;

c) That the Court award Nazomi damages or other monetary relief, including prejudgment interest, for Defendants' infringement;

d) That the Court find this to be an exceptional case entitling Nazomi to an award of attorney's fees, expenses, and costs pursuant to 35 U.S.C. § 285;

e) That the Court enjoin Defendants and their officers, directors, agents, and employees, from infringing, directly or indirectly, the '362, '436 and '160 patents;

f) That the Court award Nazomi such other and further relief as the Court deems just and appropriate.

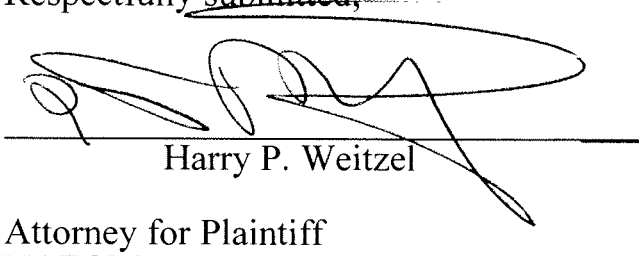
DEMAND FOR JURY TRIAL

Plaintiff respectfully requests a jury trial on all issues so triable.

Dated: October 8, 2010

PEPPER HAMILTON LLP

Respectfully submitted,



Harry P. Weitzel

Attorney for Plaintiff
NAZOMI COMMUNICATIONS, INC.

e) That the Court enjoin Defendants and their officers, directors, agents, and employees, from infringing, directly or indirectly, the '362, '436 and '160 patents;

f) That the Court award Nazomi such other and further relief as the Court deems just and appropriate.

DEMAND FOR JURY TRIAL

Plaintiff respectfully requests a jury trial on all issues so triable.

Dated: October 8, 2010

PEPPER HAMILTON LLP

Respectfully submitted,

Harry P. Weitzel

Attorney for Plaintiff
NAZOMI COMMUNICATIONS, INC.

EXHIBIT 1

US007080362B2

(12) **United States Patent**
Patel et al.

(10) **Patent No.: US 7,080,362 B2**
(45) **Date of Patent: *Jul. 18, 2006**

(54) **JAVA VIRTUAL MACHINE HARDWARE FOR RISC AND CISC PROCESSORS**

(75) Inventors: **Mukesh K. Patel**, Fremont, CA (US); **Jay Kamdar**, Cupertino, CA (US); **V. R. Ranganath**, Milipitas, CA (US)

(73) Assignee: **Nazomi Communication, Inc.**, Santa Clara, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 408 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **09/938,886**

(22) Filed: **Aug. 24, 2001**

(65) **Prior Publication Data**

US 2002/0066083 A1 May 30, 2002

Related U.S. Application Data

(63) Continuation of application No. 09/208,741, filed on Dec. 8, 1998.

(51) **Int. Cl.**
G06F 9/45 (2006.01)

(52) **U.S. Cl.** **717/139**; 717/136; 717/137; 717/118; 712/34; 712/43; 712/203; 712/209

(58) **Field of Classification Search** 717/136–140, 717/146–149, 151–153, 165, 143, 118; 712/202–203, 712/212, 244, 210, 206–209, 34, 43; 710/29
See application file for complete search history.

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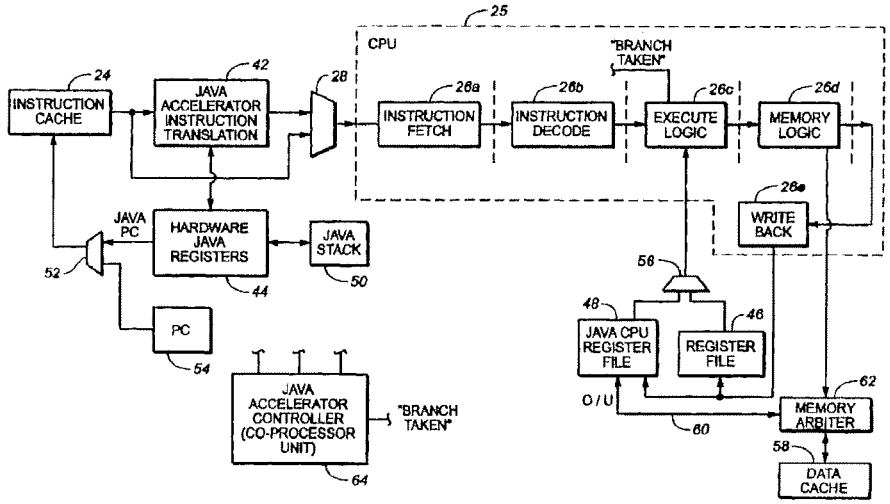
Primary Examiner—Chameli C. Das
(74) *Attorney, Agent, or Firm*—Hahn and Moodley LLP

(57) **ABSTRACT**

A hardware Java™ accelerator is provided to implement portions of the Java™ virtual machine in hardware in order to accelerate the operation of the system on Java™ bytecodes. The Java™ hardware accelerator preferably includes Java™ bytecode translation into native CPU instructions. The combination of the Java™ hardware accelerator and a CPU provides a embedded solution which results in an inexpensive system to run Java™ programs for use in commercial appliances.

99 Claims, 9 Drawing Sheets



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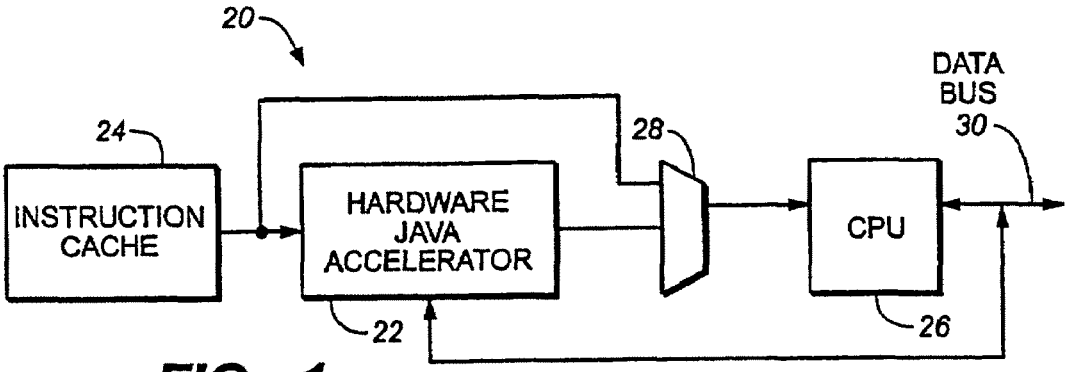
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DATA BUS
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INSTRUCTION CACHE
HARDWARE JAVA ACCELERATOR
CPU
22
26

FIG._1

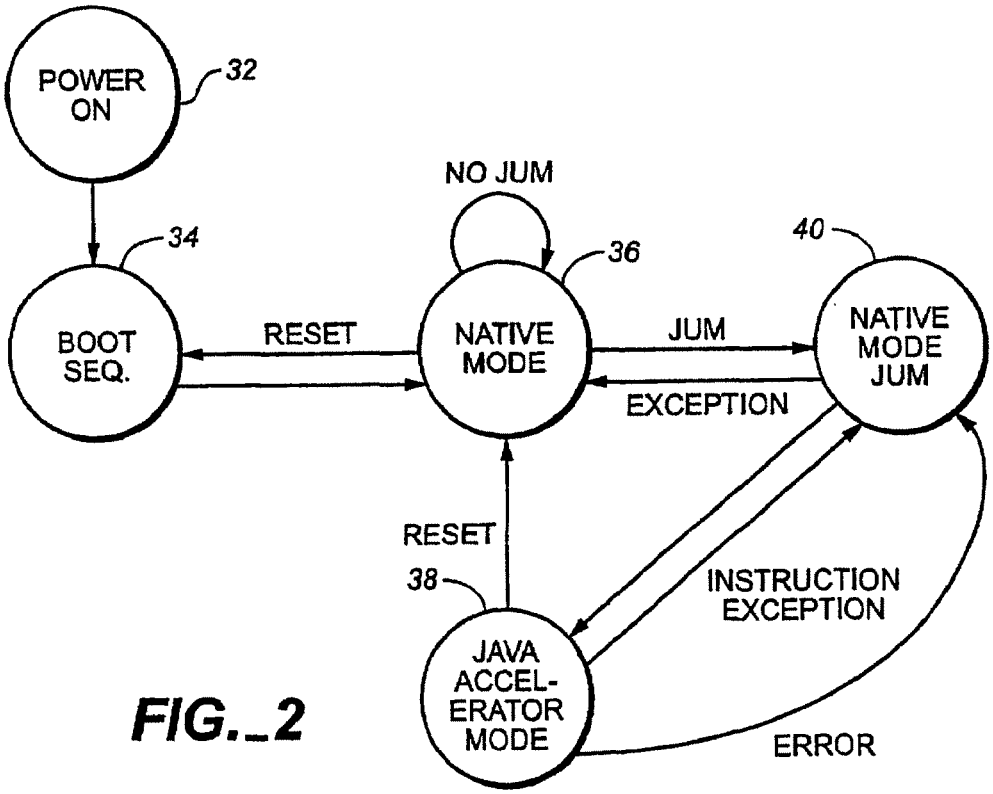
POWER ON
32
NO JUM
34
36
40
BOOT SEQ.
RESET
NATIVE MODE
JUM
NATIVE MODE JUM
EXCEPTION
RESET
38
INSTRUCTION EXCEPTION
JAVA ACCEL-ERATOR MODE
ERROR

FIG._2

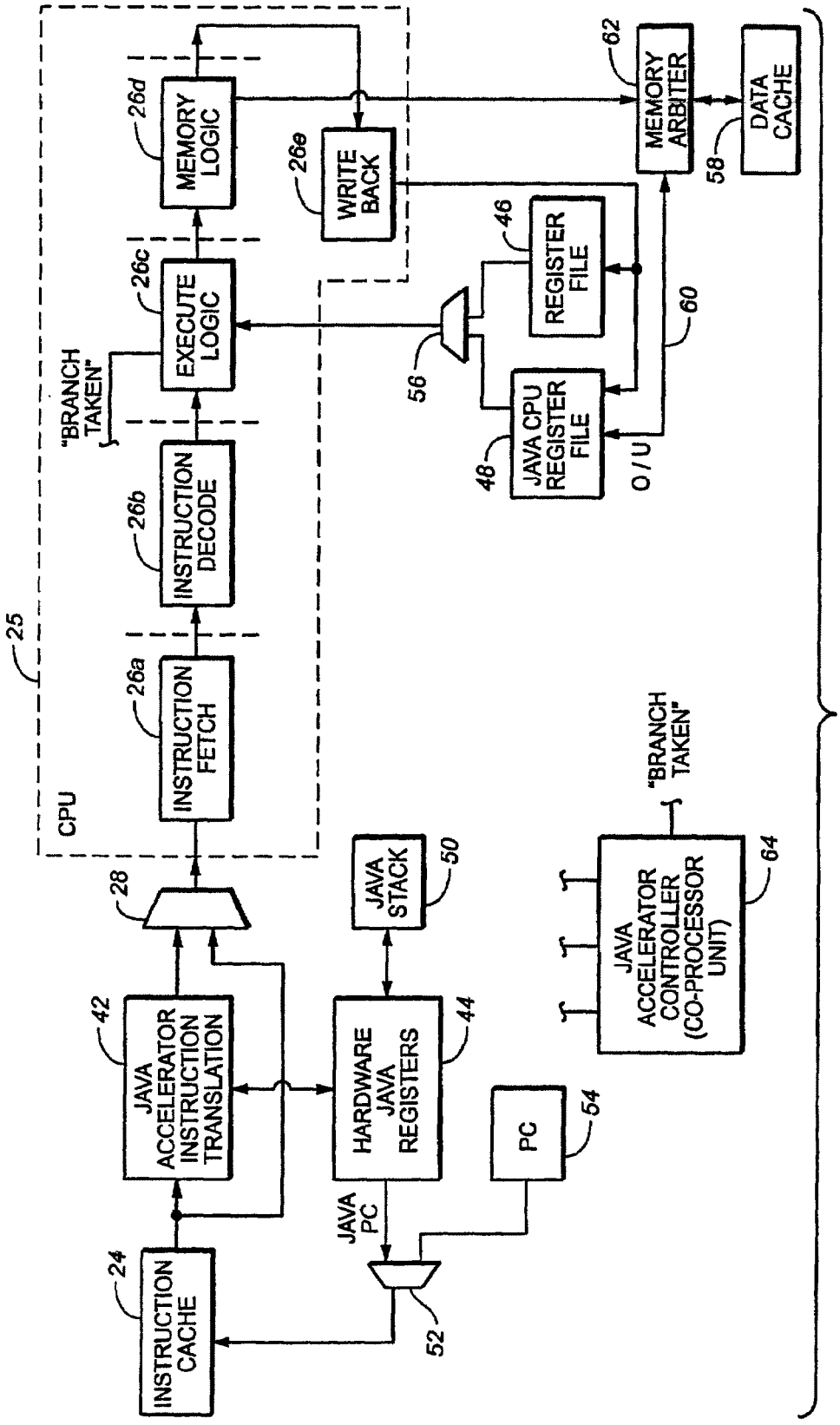
CPU
25
INSTRUCTION FETCH
26a
INSTRUCTION DECODE
26b
EXECUTE LOGIC
26c
MEMORY LOGIC
26d
WRITE BACK
26e
"BRANCH TAKEN"
28
JAVA ACCELERATOR INSTRUCTION TRANSLATION
42
HARDWARE JAVA REGISTERS
44
JAVA STACK
50
JAVA PC
52
INSTRUCTION CACHE
24
PC
54
56
REGISTER FILE
46
JAVA CPU REGISTER FILE
48
O / U
60
MEMORY ARBITER
62
DATA CACHE
58
"BRANCH TAKEN"
JAVA ACCELERATOR CONTROLLER (CO-PROCESSOR UNIT)
64

FIG._3

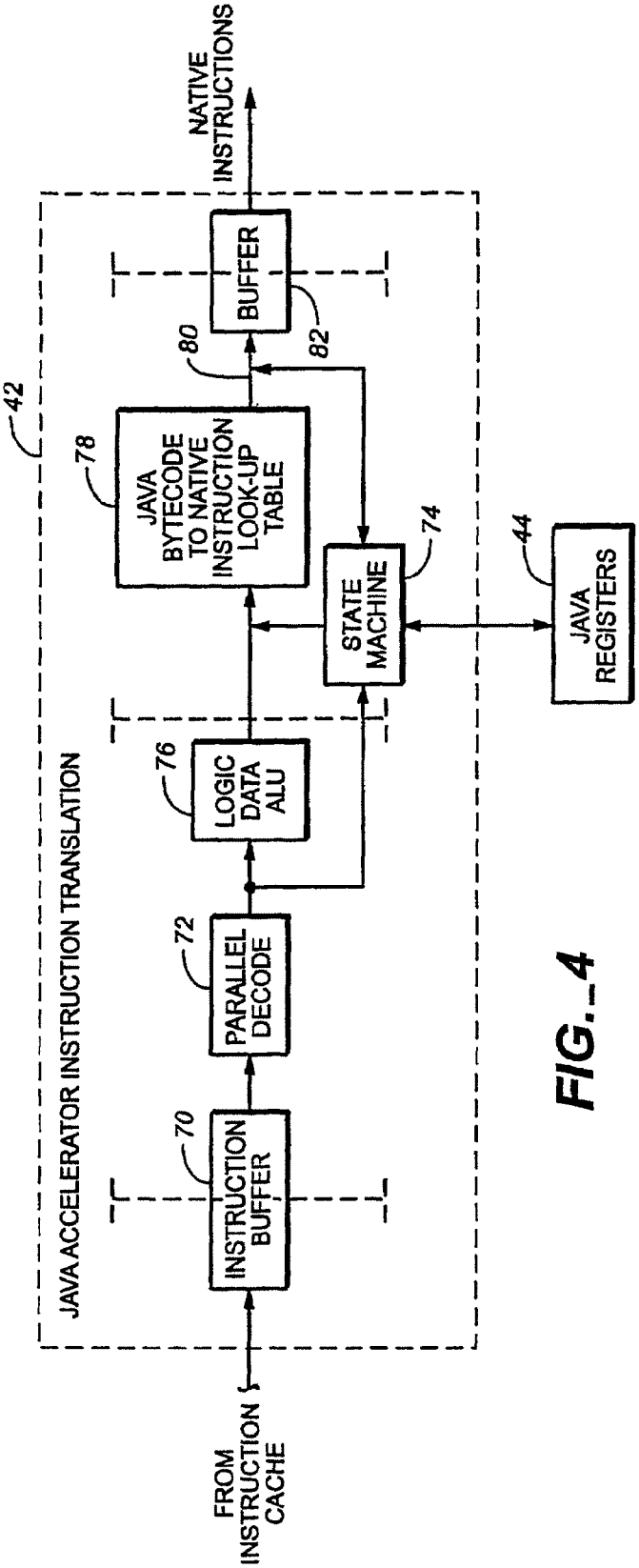
NATIVE INSTRUCTIONS
BUFFER
82
80
42
78
JAVA BYTECODE TO NATIVE INSTRUCTION LOOK-UP TABLE
74
44
STATE MACHINE
JAVA REGISTERS
76
LOGIC DATA ALU
72
PARALLEL DECODE
70
INSTRUCTION BUFFER
JAVA ACCELERATOR INSTRUCTION TRANSLATION
FROM INSTRUCTION CACHE

FIG._4

I. INSTRUCTION TRANSLATION

JAVA BYTECODE		NATIVE INSTRUCTION
iadd	⇨	ADD R1, R2

II. JAVA REGISTER

PC = VALUE A OPTOP = VALUE B (R1) VAR = VALUE C	⇨	PC = VALUE A + 1 OPTOP = VALUE B - 1 (R2) VAR = VALUE C

III. JAVA CPU REGISTER FILE

	R0	0001		R0	0001
CONTAINS VALUE OF TOP OF OPERAND STACK →	R1	0150	⇨	NOT A VALID STACK VALUE →	R1	0150
	R2	1210		CONTAINS VALUE OF THE TOP OF OPERAND STACK →	R2	1360
	R3	0007			R3	0007
	R4	0005			R4	0005
	R5	0006			R5	0006
CONTAINS FIRST VARIABLE →	R6	1221			R6	1221
	R7	1361			R7	1361

IV. MEMORY

OPTOP = VALUE B →	-	0150			0150
(VALUE B - 1)	-	1210	⇨	OPTOP = VALUE B - 1	1360
	-	0007			0007
	-	0005			0005
	-	0006			0006
	-	0001			0001
	-	4427			4427
VAR = VALUE C	-	1221		VAR = VALUE C	1221
	-	1361			1361
	-	1101			1101

FIG._5

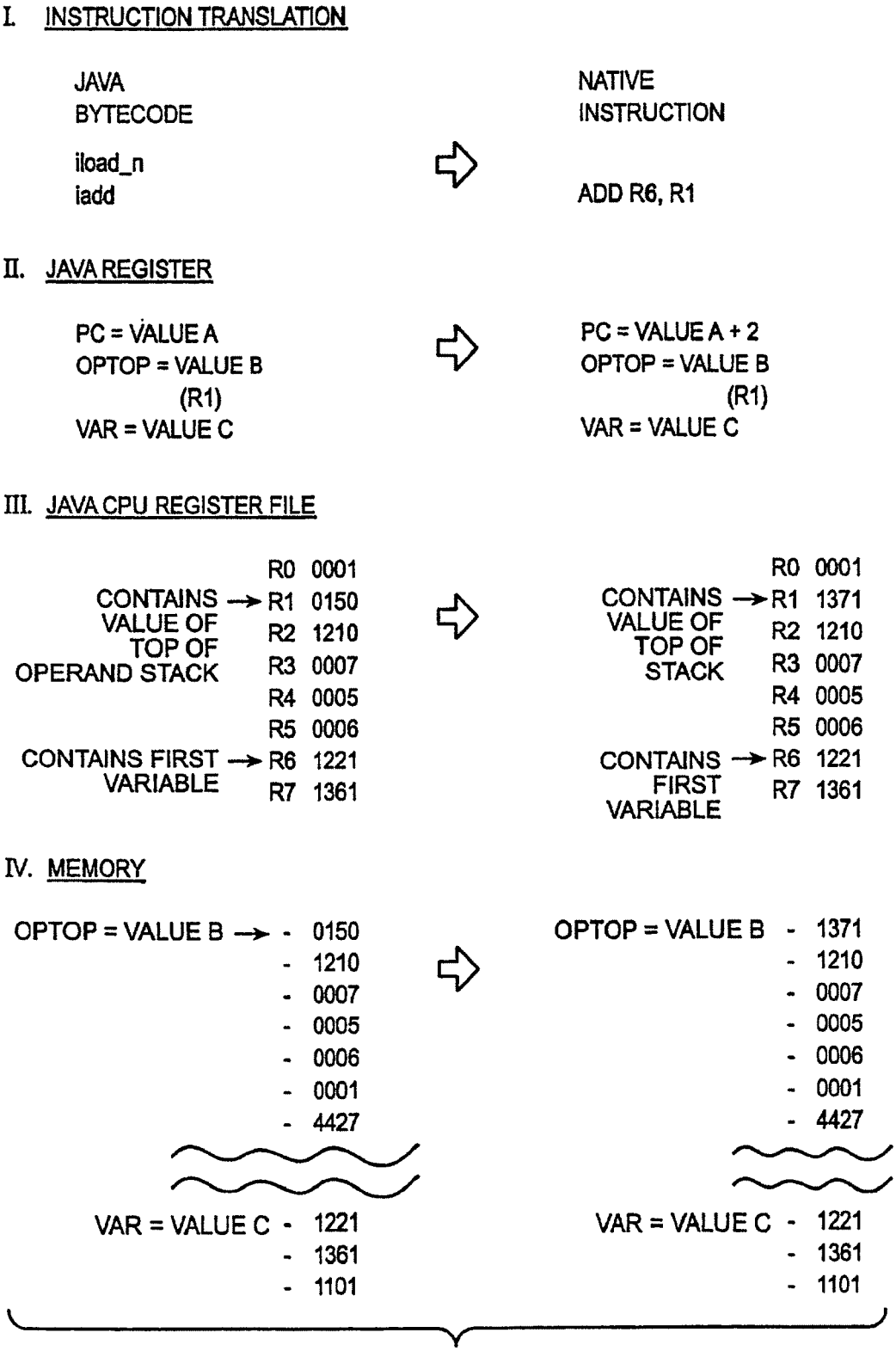
I. INSTRUCTION TRANSLATION
JAVA BYTECODE
iload_n
iadd
NATIVE INSTRUCTION
ADD R6, R1
II. JAVA REGISTER
PC = VALUE A
OPTOP = VALUE B (R1)
VAR = VALUE C
PC = VALUE A + 2
OPTOP = VALUE B (R1)
VAR = VALUE C
III. JAVA CPU REGISTER FILE
CONTAINS VALUE OF TOP OF OPERAND STACK
CONTAINS FIRST VARIABLE
R0 0001
R1 0150
R2 1210
R3 0007
R4 0005
R5 0006
R6 1221
R7 1361
CONTAINS VALUE OF TOP OF STACK
CONTAINS FIRST VARIABLE
R0 0001
R1 1371
R2 1210
R3 0007
R4 0005
R5 0006
R6 1221
R7 1361
IV. MEMORY
OPTOP = VALUE B
VAR = VALUE C
- 0150
- 1210
- 0007
- 0005
- 0006
- 0001
- 4427
- 1221
- 1361
- 1101
OPTOP = VALUE B
VAR = VALUE C
- 1371
- 1210
- 0007
- 0005
- 0006
- 0001
- 4427
- 1221
- 1361
- 1101

FIG._6

Opcodes Mnemonic	Opcode xHH	Excep Gen
nop	0x00	
aconst_null	x01	
iconst_m1	x02	
iconst_n(0-5)	x03 - x08	
lconst_n(0-1)	x09 - x0a	
fconst_n(0-2)	x0c - x0d	
dconst_n(0-1)	x0e -x0f	
bipush	x10	
sipush	x11	
ldc	x12	y
ldc_w	x13	y
ldc2_w	x14	y
iload	x15	
lload	x16	
fload	x17	
dload	x18	
aload	x19	
iload_n(0-3)	x1a - x1d	
lload_n(0-3)	x1e - x21	
fload_n(0-3)	x22 - x25	
dload_n(0-3)	x26 - x29	
aload_n(0-3)	x2a - x2d	
iaload	x2e	
laload	x2f	
faload	x30	
daload	x31	
aaload	x32	
baload	x33	
caload	x34	
saload	x35	
istore	x36	
lstore	x37	
fstore	x38	
dstroe	x39	
astroe	x3a	
istore_n(0-3)	x3b - x3e	
lstore_n(0-3)	x3f - x42	
fstore_n(0-3)	x43 - x46	
dstore_n(0-3)	x47 - x4a	
astore_n(0-3)	x4b - x4e	
iastore	x4f	
lastore	x50	
fastroe	x51	
dastore	x52	
bastore	x53	
aastore	x54	
castroe	x55	
sastore	x56	

FIG._7A

pop	x57	
pop2	x58	
dup	x59	
dup_x1	x5a	
dup_x2	x5b	
dup2	x5c	
dup2_x1	x5d	
dup2_x2	x5e	
swap	x5f	
iadd	x60	
ladd	x61	
fadd	x62	y
dadd	x63	y
isub	x64	
lsub	x65	
fsub	x66	y
dsub	x67	y
imul	x68	
lmul	x69	
fmul	x6a	y
dmul	x6b	y
idiv	x6c	y
ldiv	x6d	y
fdiv	x6e	y
ddiv	x6f	y
irem	x70	y
lrem	x71	y
frem	x72	y
drem	x73	y
ineg	x74	
lneg	x75	
fneg	x76	y
dneg	x77	y
ishl	x78	
lshl	x79	
ishr	x7a	
lshr	x7b	
iushr	x7c	
lushr	x7d	
iand	x7e	
land	x7f	
ior	x80	
lor	x81	
ixor	x82	
lxor	x83	
iinc	x84	
i2l	x85	y
i2f	x86	y
i2d	x87	y
l2l	x88	y
l2f	x89	y
l2d	x8a	y

FIG._7B

f2i	x8b	y
f2l	x8c	y
f2d	x8d	y
d2i	x8e	y
d2l	x8f	y
d2f	x90	y
i2b	x91	
i2c	x92	
i2s	x93	
lcmp	x94	y
fcmpl	x95	y
fcmpg	x96	y
dcmpl	x97	y
dcmpg	x98	y
ifeq	x99	
ifne	x9a	
iflt	x9b	
ifge	x9c	
ifgt	x9d	
ifle	x9e	
if_icmpeq	x9f	
if_icmpne	xa0	
if_icmplt	xa1	
if_acmpge	xa2	
if_cmpgt	xa3	
if_icmple	xa4	
if_acmpeq	xa5	
if_acmpne	xa6	
goto	xa7	
jsr	xa8	
ret	xa9	
tableswitch	xaa	y
lookupswitch	xab	y
ireturn	xac	
ireturn	xad	
freturn	xae	
dreturn	xaf	
areturn	xb0	
return	xb1	
getstatic	xb2	y
putstatic	xb3	y
getfield	xb4	y
putfield	xb5	y
invokevirtual	xb6	y
invokespecial	xb7	y
invokestatic	xb8	y
invokeinterface	xb9	y
xxunusedxxx	xba	y
new	xbb	y
newarray	xbc	y
anewarray	xbd	y
arraylength	xbe	y

FIG._7C

athrow	xbf	y
checkcast	xc0	y
instanceof	xc1	y
monitorenter	xc2	y
monitorexit	xc3	y
wide	xc4	y
multianewarray	xc5	y
ifnull	xc6	y
ifnonnull	xc7	y
goto_w	xc8	
jsr_w	xc9	
ldc_quick	xcb	y
ldc_w_quick	xcc	y
ldc2_w_quick	xcd	y
getfield_quick	xce	y
putfield_quick	xcf	y
getfield2_quick	xd0	y
putfield2_quick	xd1	y
getstatic_quick	xd2	y
putstatic_quick	xd3	y
gtestatic2_quick	xd4	y
putstatic2_quick	xd5	y
invokevirtual_quick	xd6	y
invokenonvirtual_quick	xd7	y
invokesuper_quick	xd8	y
invokestatic_quick	xd9	y
invokeinterface_quick	xda	y
invokevirtualobject_quick	xdb	y
new_quick	xdc	y
anewarray_quick	xde	y
multinewarray_quick	xdf	y
checkcast_quick	xe0	y
instanceof_quick	xe1	y
invokevirtual_quick_w	xe2	y
getfield_quick_w	xe3	y
putfield_quick_w	xe4	y
breakpoint	xca	y
impdep1	xfe	y
impdep2	xff	y

FIG._7D

JAVA VIRTUAL MACHINE HARDWARE FOR RISC AND CISC PROCESSORS

This application is a continuation of application Ser. No. 09/208,741 Dec. 8, 1998.

BACKGROUND OF THE INVENTION

Java™ is an object orientated programming language developed by Sun Microsystems. The Java™ language is small, simple and portable across platforms and operating systems, both at the source and at the binary level. This makes the Java™ programming language very popular on the Internet.

Java™'s platform independence and code compaction are the most significant advantages of Java™ over conventional programming languages. In conventional programming languages, the source code of a program is sent to a compiler which translates the program into machine code or processor instructions. The processor instructions are native to the system's processor. If the code is compiled on an Intel-based system, the resulting program will only run on other Intel-based systems. If it is desired to run the program on another system, the user must go back to the original source code, obtain a compiler for the new processor, and recompile the program into the machine code specific to that other processor.

Java™ operates differently. The Java™ compiler takes a Java™ program and, instead of generating machine code for a particular processor, generates bytecodes. Bytecodes are instructions that look like machine code, but aren't specific to any processor. To execute a Java™ program, a bytecode interpreter takes the Java™ bytecode converts them to equivalent native processor instructions and executes the Java™ program. The Java™ byte code interpreter is one component of the Java™ Virtual Machine.

Having the Java™ programs in bytecode form means that instead of being specific to any one system, the programs can run on any platform and any operating system as long a Java™ Virtual Machine is available. This allows a binary bytecode file to be executable across platforms.

The disadvantage of using bytecodes is execution speed. System specific programs that run directly on the hardware from which they are compiled, run significantly faster that Java™ bytecodes, which must be processed by the Java™ Virtual Machine. The processor must both convert the Java™ bytecodes into native instructions in the Java™ Virtual Machine and execute the native instructions.

One way to speed up the Java™ Virtual Machine is by techniques such as the "Just in Time" (JIT) interpreter, and even faster interpreters known as "Hot Spot JITs" interpreters. The JIT versions all result in a JIT compile overhead to generate native processor instructions. These JIT interpreters also result in additional memory overhead.

The slow execution speed of Java™ and overhead of JIT interpreters have made it difficult for consumer appliances requiring local-cost solutions with minimal memory usage and low energy consumption to run Java™ programs. The performance requirements for existing processors using the fastest JITs more than double to support running the Java™ Virtual Machine in software. The processor performance requirements could be met by employing superscalar processor architectures or by increasing the processor clock frequency. In both cases, the power requirements are dramatically increased. The memory bloat that results from JIT techniques, also goes against the consumer application requirements of low cost and low power.

It is desired to have an improved system for implementing Java™ programs that provides a low-cost solution for running Java™ programs for consumer appliances.

SUMMARY OF THE INVENTION

The present invention generally relates to a Java™ hardware accelerator which can be used to quickly translate Java™ bytecodes into native instructions for a central processing unit (CPU). The hardware accelerator speeds up the processing of the Java™ bytecodes significantly because it removes the bottleneck which previously occurred when the Java™ Virtual Machine is run in software on the CPU to translate Java™ bytecodes into native instructions.

In the present invention, at least part of the Java™ Virtual Machine is implemented in hardware as the Java™ hardware accelerator. The Java™ hardware accelerator and the CPU can be put together on a single semiconductor chip to provide an embedded system appropriate for use with commercial appliances. Such an embedded system solution is less expensive than a powerful superscalar CPU and has a relatively low power consumption.

The hardware Java™ accelerator can convert the stack-based Java™ bytecodes into a register-based native instructions on a CPU. The hardware accelerators of the present invention are not limited for use with Java™ language and can be used with any stack-based language that is to be converted to register-based native instructions. Also, the present invention can be used with any language that uses instructions, such as bytecodes, which run on a virtual machine.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention may be further understood from the following description in conjunction with the drawings.

FIG. **1** is a diagram of the system of the present invention including the hardware Java™ accelerator.

FIG. **2** is a diagram illustrating the use of the hardware Java™ accelerator of the present invention.

FIG. **3** is a diagram illustrating some the details of a Java™ hardware accelerator of one embodiment of the present invention.

FIG. **4** is a diagram illustrating the details of one embodiment of a Java™ accelerator instruction translation in the system of the present invention.

FIG. **5** is a diagram illustration the instruction translation operation of one embodiment of the present invention.

FIG. **6** is a diagram illustrating the instruction translation system of one embodiment of the present invention using instruction level parallelism.

FIGS. **7**A–7D are the tables showing the possible lists of bytecodes which can cause exceptions in a preferred embodiment.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. **1** is a diagram of the system **20** showing the use of a hardware Java™ accelerator **22** in conjunction with a central processing unit **26**. The Java™ hardware accelerator **22** allows part of the Java™ Virtual Machine to be implemented in hardware. This hardware implementation speeds up the processing of the Java™ byte codes. In particular, in a preferred embodiment, the translation of the Java™ bytecodes into native processor instructions is at least partially done in the hardware Java™ accelerator **22**. This translation

has been part of a bottleneck in the Java™ Virtual Machine when implemented in software. In FIG. **1**, instructions from the instruction cache **24** or other memory is supplied to the hardware Java™ accelerator **22**. If these instruction are Java™ bytecode, the hardware Java™ accelerator **22** can convert these bytecodes into native processor instruction which are supplied through the multiplexer **28** to the CPU. If a non-Java™ code is used, the hardware accelerator can be by-passed using the multiplexer **26**.

The Java™ hardware accelerator can do, some or all of the following tasks:

1. Java™ bytecode decode;
2. identifying and encoding instruction level parallelism (ILP), wherever possible;
3. translating bytecodes to native instructions;
4. managing the Java™ stack on a register file associated with the CPU or as a separate stack;
5. generating exceptions on instructions on predetermined Java™ byte codes;
6. switching to native CPU operation when native CPU code is provided;
7. performing bounds checking on array instructions; and
8. managing the variables on the register file associated with the CPU.

In a preferred embodiment, the Java™ Virtual Machine functions of bytecode interpreter, Java™ register, and Java™ stack are implemented in the hardware Java™ accelerator. The garbage collection heap and constant pool area can be maintained in normal memory and accessed through normal memory referencing.

The major advantages of the Java™ hardware accelerator is to increase the speed in which the Java™ Virtual Machine operates, and allow existing native language legacy applications, software base, and development tools to be used. A dedicated microprocessor in which the Java™ bytecodes were the native instructions would not have accesss to those legacy applications.

Although the Java™ hardware accelerator is shown in FIG. **1** as separate from the central processing unit, the Java™ hardware accelerator can be incorporated into a central processing unit. In that case, the central processing unit has a Java™ hardware accelerator subunit to translate Java™ bytecode into the native instructions operated on by the main portion of the CPU.

FIG. **2** is a state machine diagram that shows the operation of one embodiment of the present invention. Block **32** is the power-on state. During power-on, the multiplexer **28** is set to bypass the Java™ hardware accelerator. In block **34**, the native instruction boot-up sequence is run. Block **36** shows the system in the native mode executing native instructions and by-passing the Java™ hardware accelerator.

In block **38**, the system switches to the Java™ hardware accelerator mode. In the Java™ hardware accelerator mode, Java™ bytecode is transferred to the Java™ hardware accelerator **22**, converted into native instructions then sent to the CPU for operation.

The Java™ accelerator mode can produce exceptions at certain Java™ bytecodes. These bytecodes are not processed by the hardware accelerator **22** but are processed in the CPU **26**. As shown in block **40**, the system operates in the native mode but the Java™ Virtual Machine is implemented in the CPU which does the bytecode translation and handles the exception created in the Java™ accelerator mode.

The longer and more complicated bytecodes that are difficult to handle in hardware can be selected to produce the exceptions.

FIGS. **7A–7D** are the tables showing the possible lists of bytecodes which can cause exceptions in a preferred embodiment.

FIG. **3** is a diagram illustrating details of one embodiment of the Java™ hardware accelerator of the present invention. The Java™ hardware accelerator includes Java™ accelerator instruction translation hardware **42**. The instruction translation Unit **42** is used to convert Java™ bytecodes to native instructions. One embodiment of the Java™ accelerator instruction translation hardware **42** is described in more detail below with respect to FIG. **4**. This instruction translation hardware **42** uses data stored in hardware Java™ registers **44**. The hardware Java™ Registers store the Java™ Registers defined in the Java™ Virtual Machine. The Java™ Registers contain the state of the Java™ Virtual Machine, affect its operation, and are updated after each bytecode is executed. The Java™ registers in the Java™ virtual machine include the PC, the program counter indicating what bytecode is being executed; Optop, a pointer to the top of the operand stack; Frame, a pointer to the execution environment of the current method; and Vars, a pointer to the first local variable available of the currently executing method. The virtual machine defines these registers to be a single 32-bit word wide. The Java™ registers are also stored in the Java™ stack which can be implemented as the hardware Java™ stack **50** or the Java™ stack can be stored into the CPU associated register file.

In a preferred embodiment, the hardware Java™ registers **44** can include additional registers for the use of the instruction translation hardware **42**. These registers can include a register indicating a switch to native instructions and a register indicating the version number of the system.

The Java™ PC can be used to obtain bytecode instructions from the instruction cache **24**. In one embodiment the Java™ PC is multiplexed with the normal program counter **54** of the central processing unit **26** in multiplexer **52**. The normal PC **54** is not used during the operation of the Java™ hardware bytecode translation. In another embodiment, the normal program counter **54** is used as the Java™ program counter.

The Java™ registers are a part of the Java™ Virtual Machine and should not be confused with the general registers **46** or **48** which are operated upon by the central processing unit **26**. In one embodiment, the system uses the traditional CPU register file **46** as well as a Java™ CPU register file **48**. When native code is being operated upon the multiplexer **56** connects the conventional register file **46** to the execution logic **26***c* of the CPU **26**. When the Java™ hardware accelerator is active, the Java™ CPU register file **48** substitutes for the conventional CPU register file **46**. In another embodiment, the conventional CPU register file **46** is used.

As described below with respect to FIGS. **3** and **4**, the Java™ CPU register file **48**, or in an alternate embodiment the conventional CPU register file **46**, can be used to store portions of the operand stack and some of the variables. In this way, the native register-based instructions from the Java™ accelerator instruction translator **42** can operate upon the operand stack and variable values stored in the Java™ CPU register file **48**, or the values stored in the conventional CPU register file **46**. Data can be written in and out of the Java™ CPU register file **48** from the data cache or other memory **58** through the overflow/underflow line **60** connected to the memory arbiter **62**. The overflow/underflow transfer of data to and from the memory to can done concurrently with the CPU operation. Alternately, the overflow/underflow transfer can be done explicitly while the

CPU is not operating. The overflow/underflow bus **60** can be implemented as a tri-state bus or as two separate buses to read data in and write data out of the register file when the Java™ stack overflows or underflows.

The register files for the CPU could alternately be implemented as a single register file with native instructions used to manipulate the loading of operand stack and variable values to and from memory. Alternately, multiple Java™ CPU register files could be used: one register file for variable values, another register file for the operand stack values, and another register file for the Java™ frame stack holding the method environment information.

The Java™ accelerator controller (co-processing unit) **64** can be used to control the hardware Java™ accelerator, read in and out from the hardware Java™ registers **44** and Java™ stack **50**, and flush the Java™ accelerator instruction translation pipeline upon a "branch taken" signal from the CPU execute logic **26***c*.

The CPU **26** is divided into pipeline stages including the instruction fetch **26***a*, instruction decode **26***b*, execute logic **26***c*, memory access logic **26***d*, and writeback logic **26***e*. The execute logic **26***c* executes the native instructions and thus can determine whether a branch instruction is taken and issue the "branch taken" signal.

FIG. **4** illustrates an embodiment of a Java™ accelerator instruction translator which can be used with the present invention. The instruction buffer **70** stores the bytecode instructions from the instruction cache. The bytecodes are sent to a parallel decode unit **72** which decodes multiple bytecodes at the same time. Multiple bytecodes are processed concurrently in order to allow for instruction level parallelism. That is, multiple bytecodes may be converted into a lesser number of native instructions.

The decoded bytecodes are sent to a state machine unit **74** and Arithmetic Logic Unit (ALU) **76**. The ALU **76** is provided to rearrange the bytecode instructions to make them easier to be operated on by the state machine **74**. The state machine **74** converts the bytecodes into native instructions using the look-up table **78**. Thus, the state machine **74** provides an address which indicates the location of the desired native instruction in the look-up table **78**. Counters are maintained to keep a count of how many entries have been placed on the operand stack, as well as to keep track of the top of the operand stack. In a preferred embodiment, the output of the look-up table **78** is augmented with indications of the registers to be operated on at line **80**. The register indications are from the counters and interpreted from bytecodes. Alternately, these register indications can be sent directly to the Java™ CPU register file **48** shown in FIG. **3**.

The state machine **74** has access to the Java™ registers in **44** as well as an indication of the arrangement of the stack and variables in the Java™ CPU register file **48** or in the conventional CPU register file **46**. The buffer **82** supplies the translated native instructions to the CPU.

The operation of the Java™ hardware accelerator of one embodiment of the present invention is illustrated in FIGS. **5** and **6**. FIG. **5**, section I shows the instruction translation of the Java™ bytecode. The Java™ bytecode corresponding to the mnemonic iadd is interpreted by the Java™ virtual machine as an integer operation taking the top two values of the operand stack, adding them together and pushing the result on top of the operand stack. The Java™ translating machine translates the Java™ bytecode into a native instruction such as the instruction ADD R1, R2. This is an instruction native to the CPU indicating the adding of value in register R1 to the value in register R2 and the storing of this result in register R2. R1 and R2 are the top two entries in the operand stack.

As shown in FIG. **5**, section II, the Java™ register includes a PC value of "Value A" that is incremented to "Value A+1". The Optop value changes from "Value B" to "Value B−1" to indicate that the top of the operand stack is at a new location. The Vars value which points to the top of the variable list is not modified. In FIG. **5**, section III, the contents of a Java™ CPU register file, such as the Java™ CPU register file **48** in FIG. **3**, is shown. The Java™ CPU register file starts off with registers R**0**–R**5** containing operand stack values and registers R**6**–R**7** containing variable values. Before the operation of the native instruction, register R**1** contains the top value of the operand stack. Register R**6** contains the first variable. After the execution of the native instruction, register R**2** now contains the top value of the operand stack. Register R**1** no longer contains a valid operand stack value and is available to be overwritten by a operand stack value from the memory sent across the overflow/underflow line **60** or from the bytecode stream.

FIG. **5**, section IV shows the memory locations of the operand stack and variables which can be stored in the data cache **58** or in main memory. For convenience, the memory is illustrated without illustrating any virtual memory scheme. Before the native instruction executes, the address of the top of the operand stack, Optop, is "Value B". After the native instruction executes, the address of the top of the operand stack is "Value B−1" containing the result of the native instruction. Note that the operand stack value "4427" can be written into register R**1** across the overflow/underflow line **60**. Upon a switch back to the native mode, the data in the Java™ CPU register file **48** should be written to the data memory.

Consistency must be maintained between the Hardware Java™ Registers **44**, the Java™ CPU register file **48** and the data memory. The CPU **26** and Java™ Accelerator Instruction Translation Unit **42** are pipelined and any changes to the hardware Java™ registers **44** and changes to the control information for the Java™ CPU register file **48** must be able to be undone upon a "branch taken" signal. The system preferably uses buffers (not shown) to ensure this consistency. Additionally, the Java™ instruction translation must be done so as to avoid pipeline hazards in the instruction translation unit and CPU.

FIG. **6** is a diagram illustrating the operation of instruction level parallelism with the present invention. In FIG. **6** the Java™ bytecodes iload_n and iadd are converted by the Java™ bytecode translator to the single native instruction ADD R**6**, R**1**. In the Java™ Virtual Machine, iload_n pushes the top local variable indicated by the by the Java™ register VAR onto the operand stack.

In the present invention the Java™ hardware translator can combine the iload_n and iadd bytecode into a single native instruction. As shown in FIG. **6**, section II, the Java™ Register, PC, is updated from "Value A" to "Value A+2". The Optop value remains "value B". The value Var remains at "value C".

As shown in FIG. **6**, section III, after the native instruction ADD R**6**, R**1** executes the value of the first local variable stored in register R**6**, "1221", is added to the value of the top of the operand stack contained in register R**1** and the result stored in register R**1**. In FIG. **6**, section IV, the Optop value does not change but the value in the top of the register contains the result of the ADD instruction, **1371**.

The Java™ hardware accelerator of the present invention is particularly well suited to a embedded solution in which

the hardware accelerator is positioned on the same chip as the existing CPU design. This allows the prior existing software base and development tools for legacy applications to be used. In addition, the architecture of the present embodiment is scalable to fit a variety of applications ranging from smart cards to desktop solutions. This scalability is implemented in the Java™ accelerator instruction translation unit of FIG. **4**. For example, the lookup table **78** and state machine **74** can be modified for a variety of different CPU architectures. These CPU architectures include reduced instruction set computer (RISC) architectures as well as complex instruction set computer (CISC) architectures. The present invention can also be used with superscalar CPUs or very long instruction word (VLIW) computers.

While the present invention has been described with reference to the above embodiments, this description of the preferred embodiments and methods is not meant to be construed in a limiting sense. For example, the term Java™ in the specification or claims should be construed to cover successor programming languages or other programming languages using basic Java™ concepts (the use of generic instructions, such as bytecodes, to indicate the operation of a virtual machine). It should also be understood that all aspects of the present invention are not to be limited to the specific descriptions, or to configurations set forth herein. Some modifications in form and detail the various embodiments of the disclosed invention, as well as other variations in the present invention, will be apparent to a person skilled in the art upon reference to the present disclosure. It is therefore contemplated that the following claims will cover any such modifications or variations of the described embodiment as falling within the true spirit and scope of the present invention.

We claim:

1. A method for processing instructions in a central processing unit (CPU) capable of executing instructions of a plurality of instruction sets, including a stack-based and a register-based instruction set, the method, comprising:

maintaining data for register-based instructions from the register-based instruction set and an operand stack for operands associated with stack-based instructions from the stack-based instruction set in a first register file, wherein at least some of the operands are moved between the register file and memory via at least one of an overflow and underflow mechanism;

maintaining an indication of a depth of the operand stack; and

processing the register-based instructions including generating a first output, and processing the first output in an execution unit using the data from the first register file; and

processing the stack-based instructions including generating a second output, and processing the second output in the execution unit using the operands from the first register file; and generating exceptions in respect of selected stack-based instructions.

2. The method of claim **1**, further comprising storing variables associated with the stack-based instructions in a second register file.

3. The method of claim **2**, further comprising storing virtual machine registers in a third register file.

4. The method of claim **3**, wherein the first, second, and third register files are the same register file.

5. The method of claim **4**, wherein the operand stack is maintained in a first portion of the register file, and variables associated with the stack-based instructions are maintained in a second portion of the register file.

6. The method of claim **1**, wherein the overflow mechanism generates an overflow indication for the stack-based operands.

7. The method of claim **1**, wherein the underflow mechanism generates an underflow indication for the stack-based operands.

8. The method of claim **1**, further comprising generating a branch taken indication in respect of a selected stack-based branch instruction.

9. The method of claim **8**, further comprising flushing at least part of a pipeline associated with the processing of the selected stack-based instructions if the branch taken indication is generated.

10. The method of claim **8**, wherein the selected stack-based branch instruction is selected from the group consisting of ifeq, ifne, ifit, ifge, ifgt, ifle, if_icmpeq, if_icmpne, if_icmplt, if_acmpge, if_cmpgt, if_icmple, if_acmpeq, if_acmpne, ifnull, ifnonull, lcmp, fcmpl, fcmpg, dcmpl, and dcmpg.

11. The method of claim **1**, wherein a memory arbiter is used to facilitate at least one of a loading and a storing of operands between the register file and the memory via the at least one of the overflow and underflow mechanism.

12. The method of claim **1**, wherein at least one of the operands is moved between the register file and the memory as a result of executing at least one of a store and load operation due to at least one of the overflow and underflow indication.

13. The method of claim **11** or claim **12**, wherein the memory is a data cache.

14. The method of claim **12**, wherein executing the load or the store operation is due to executing a load or a store instruction associated with the register-based instruction set.

15. The method of claim **1**, further comprising further processing the selected stack-based instructions for which exceptions were generated using the register-based instruction set.

16. The method of claim **15**, wherein the further processing occurs within a virtual machine.

17. The method of claim **15** or claim **16**, further comprising reverting to processing the stack-based instructions after the further processing.

18. The method of claim **1**, wherein instructions of the stack-based instruction set include virtual machine bytecodes.

19. The method of claim **1**, wherein a common program counter register is used for the plurality of instruction sets.

20. The method of claim **1**, wherein a program counter for each of the plurality of instruction sets is in at least one or more program counter registers.

21. The method of claim **19** or claim **20**, wherein the program counter register is part of a register file for the CPU.

22. The method of claim **1**, wherein instructions for the plurality of instruction sets are stored in a shared instruction cache.

23. The method of claim **1**, wherein the CPU maintains an indication of which registers in the register file contain operands associated with the stack-based instructions.

24. The method of claim **23**, wherein at least a top two operands of the operand stack in the register file are referenced when executing the stack-based instructions.

25. The method of claim **1**, further comprising maintaining a counter that counts how many operands are placed in the operand stack.

26. The method of claim 1, further comprising keeping track of the top of the operand stack.

27. A method for processing instructions in a central processing unit (CPU), the method comprising:

decoding instructions of a stack-based instruction set;

maintaining an operand stack for operands associated with the instructions of the stack-based instruction set in a register file including moving at least some operands between the register file and memory via at least one of an overflow and underflow mechanism;

decoding instructions of a register-based instruction set;

maintaining data associated with the instructions of the register-based instruction set in the register file;

sending an output of the decoding of the instructions of the stack and register-based instruction sets, to an execution unit; and

processing the output in the execution unit, including processing exceptions in respect of selected instructions of the stack-based instruction set in a virtual machine.

28. The method of claim 27, further comprising setting at least one bit to indicate which instruction set to use for the processing.

29. The method of claim 28, wherein the processing of the exceptions is performed using the register-based instruction set.

30. The method of claim 28, wherein the at least one bit is set in respect of those instructions of the stack-based instruction set for which an exception is generated.

31. The method of claim 30, further comprising maintaining a program counter for the stack-based instruction set and a program counter for the register-based instruction set in the same register.

32. The method of claim 30, wherein a program counter for instructions of the stack-based and register-based instruction sets are in at least one or more registers.

33. The method of claim 27, wherein the output of decoding-instructions of the stack-based instruction set is sent to the execution unit via the second decode unit.

34. The method of claim 27, wherein a memory arbiter is used to facilitate the loading and storing of operands between the register file and memory via the at least one of an overflow and underflow mechanism.

35. The method of claim 34, wherein the memory includes a data cache.

36. The method of claims 27, further comprising, prior to processing the output in the execution unit, processing the instructions of the stack-based instruction set in a hardware accelerator.

37. The method of claims 36, wherein processing the instructions of stack-based instruction set in the hardware accelerator comprising generating the exceptions, each in respect of a selected instruction of the stack-based instruction set.

38. A method, comprising:

switching a processing system to an accelerator mode, wherein stack-based instructions are executed directly in hardware;

generating an exception in respect of a selected stack-based instruction while in the accelerator mode;

switching the processing system to a first native mode in which the exception is handled within a virtual machine by executing a register-based instruction; and

switching the processing system to a second native mode upon a further exception generated while in the first native mode, wherein in the second native mode the virtual machine is non-operative and handling of the further exception is by executing a register-based instruction.

39. The method of claim 38, wherein the stack-based instructions include virtual machine bytecodes.

40. In a processing system, comprising a central processing unit (CPU) having an execution unit and a register file, and being capable of processing instructions of a plurality of instruction sets including a register-based instruction set and a stack-based instruction set, wherein an operand stack for operands associated with the stack-based instruction set is maintained in the register file, and the operands are moved between the register file and memory due to at least one of an overflow and underflow mechanism, and wherein the processing system further comprises a first state in which the CPU processes instructions using the register-based instruction set without a virtual machine, a second state in which the CPU processes using the non-stack-based instruction set within a virtual machine, and a third state in which the CPU processes instructions using the stack-based instruction set within the virtual machine, a method of operating the CPU comprising:

switching the processing system to the first state due to at least one of a reset command and a power-on condition;

switching the CPU to the second state;

processing instructions in the second state; and

upon encountering an exception while processing the instructions in the second state, switching the CPU to the first state.

41. The method of claim 40, further comprising switching the CPU from the second state to the third state.

42. The method of claim 41, further comprising, upon receiving a reset command, switching the CPU from the third state to the first state.

43. The method of claim 41, further comprising, upon encountering an exception while processing instructions in the third state, switching the CPU from the third state to the second state.

44. The method of claim 41, wherein the switching to the third state is while in a virtual machine to execute the stack-based instruction set.

45. The method of claim 40, further comprising setting at least one bit to indicate to the CPU which instruction set to use.

46. The method of claim 27, claim 38, or claim 40, wherein the stack-based instructions include virtual machine byte codes.

47. The method of claim 1, claim 27, claim 38, or claim 40, wherein the stack-based instruction generating an exception is selected_from the group consisting of tableswitch, lookupswitch, getstatic, putstatic, getfield, putfield, invokevirtual, invokespecial, invokestatic, invokeinterface, new, newarray, arraylength, athrow, checkcast, instanceof, monitorenter, monitorexit, breakpoint, anewarray, imdep1, and imdep2.

48. A central processing unit (CPU), capable of executing a plurality of instruction sets comprising:

an execution unit and associated register file, the execution unit to execute instructions of a plurality of instruction sets, including a stack-based and a register-based instruction set;

a mechanism to maintain at least some data for the plurality of instruction sets in the register file including maintaining an operand stack for the stack-based instructions in the register file and an indication of a depth of the operand stack;

a stack control mechanism that includes at least one of an overflow and underflow mechanism, wherein at least some of the operands are moved between the register file and memory; and

a mechanism to generate an exception in respect of selected stack-based instructions.

49. The central processing unit of claim **48**, wherein the register file is a first register file, the central processing unit further comprising a second register file to store variables associated with the stack-based instructions.

50. The central processing unit of claim **49**, further comprising a third register file to store virtual machine registers.

51. The central processing unit of claim **50**, wherein the first, the second, and the third register files are the same register file.

52. The central processing unit of claim **51**, wherein the operand stack is maintained in a first portion of the register file, and variables associated with the stack-based instructions are maintained in a second portion of the register file.

53. The central processing unit of claim **48**, wherein the overflow mechanism generates an overflow indication for the operand stack.

54. The central processing unit of claim **53**, wherein the underflow mechanism generates an underflow indication for the operand stack.

55. The central processing unit of claim **48**, further comprising a mechanism to generate a branch taken indication in respect of a selected stack-based instruction.

56. The central processing unit of claim **55**, further comprising a mechanism to flush at least part of a pipeline associated with the processing of the selected stack-based instruction, if the branch taken instruction is generated.

57. The central processing unit of claim **48**, further comprising a memory arbiter to facilitate at least one of a loading and a storing of operands between the register file and the memory and via the stack control mechanism.

58. The central processing unit of claim **48**, wherein the operands are moved between the register file and the memory as a result of executing at least one of a load and a store operation due to at least one of the overflow and underflow indication.

59. The central processing unit of claim **58**, wherein executing at least one of the load and store operation is due to executing a load or a store instruction associated with the register-based instruction set.

60. The central processing unit of claim **48**, wherein the memory is a data cache.

61. The central processing unit of claim **55**, wherein the selected stack-based instruction is selected from the group consisting of ifeq, ifne, iflt, ifge, ifgt, ifle, if_icmpeq, if_icmpne, if_icmplt, if_acmpge, if_cmpgt, if_icmple, if_acmpeq, if_acmpne, ifnull, ifnonull, lcmp, fcmpl, fcmpg, dcmpl, and dcmpg.

62. The central processing unit of claim **48**, further comprising further processing the selected stack-based instructions for which exceptions were generated using the register-based instruction set.

63. The central processing unit of claim **62**, wherein the further processing occurs within a virtual machine.

64. The central processing unit of claim **63**, wherein the execution unit reverts to processing the stack-based instructions, after the further processing.

65. The central processing unit of claim **48**, wherein instructions of the stack-based instruction set includes virtual machine bytecodes.

66. The central processing unit of claim **48**, further comprising a common program counter register for the plurality of instruction sets.

67. The central processing unit of claim **48**, further comprising at least one program counter register to implement a program counter for each of the plurality of instruction sets.

68. The central processing unit of claims **66** or claim **67**, wherein at least some of the program counter is implemented within the register file.

69. The central processing unit of claim **48**, wherein instructions for the plurality of instruction sets are stored in a shared instruction cache.

70. The central processing unit of claim **48**, further comprising a mechanism that maintains an indication of which registers in the register file contain operands associated with the stack-based instructions.

71. The central processing unit of claim **70**, wherein at least a top two operands of the operand stack in the register file are referenced when executing the stack-based instructions.

72. The central processing unit of claim **48**, further comprising for the instructions of the stack-based instruction set, processing said instructions in a hardware accelerator to process instructions of the stack-back instruction set prior to the processing of said instructions in the execution unit.

73. The central processing unit of claim **72**, wherein the hardware accelerator generates the exceptions.

74. A central processing unit (CPU) comprising:

a decoding mechanism to decode instructions of a plurality of instruction sets including a -stack-based instruction set and a register-based instruction set;

a register file, wherein an operand stack to store operands associated with instructions of the stack-based instruction set is maintained; and wherein data associated with instructions of the register-based instruction set is maintained;

at least one of an overflow and underflow mechanism to cause the operands to—be moved between the register file and memory; and

an execution unit that processes the output of the decoding of the instructions of the stack-based instruction set, and the decoding of the instructions of the register-based instruction set, including processing exceptions in respect of selected instructions of the stack-based instruction set within a virtual machine.

75. The central processing unit of claim **74**, further comprising a mechanism to set at least one bit to indicate which instruction set is to be used for the processing.

76. The central processing unit of claim **75**, wherein the at least one bit is set in respect of those instructions of the stack-based instruction set for which an exception is generated.

77. The central processing unit of claim **75**, further comprising a register within which a program counter for the stack-based instruction set and a program counter for the register-based instruction set is maintained.

78. The central processing unit of claim **74**, wherein an indication of the depth of the operand stack for the stack-based_instruction set is maintained.

79. The central processing unit of claim **48** or claim **78**, further comprising a counter to count how many operands are in the operand stack.

80. The central processing unit of claim **48** or claim **78**, further comprising a mechanism to keep track of the top of the operand stack.

81. The central processing unit of claim 74, wherein the decode unit comprises a first subunit and a second subunit, and wherein the first subunit decodes instructions of the stack-based instruction set and sends an output of the decoding to the execution unit via the second subunit.

82. The central processing unit of claim 74, further comprising a memory arbiter that facilitates at least one of the loading or storing of operands between the register file and memory via at least one of an overflow and underflow mechanism.

83. The central processing unit of claim 82, wherein the memory includes a data cache.

84. The central processing unit of claim 74, further comprising for the instructions of the stack-based instruction set, processing said instructions in a hardware accelerator to process instructions of the stack-back instruction set prior to the processing of said instructions in the execution unit.

85. The central processing unit of claim 84, wherein the hardware accelerator generates the exceptions.

86. A processing system, comprising:

an accelerator mode in which a central processing unit (CPU) of the processing system processes stack-based instructions directly in hardware;

a first native mode in which the processing system processes instructions using a non-stack-based instruction set within a virtual machine; and

a second native mode in which the processing system processes instructions using non-stack-based instructions, in which the virtual machine is non-operative, wherein

the processing system is switched to the accelerator mode to process stack-based instructions while in the accelerator mode, the processing of the stack-based instructions including generating an exception in respect of a selected stack-based instruction while in the accelerator mode, and switching to the first native mode in which the selected stack-based instruction for which the exception was generated is further processed within the virtual machine using the non-stack-based instruction set, and wherein if an exception is generated while in the first native mode, the processing system switches to the second native mode.

87. A processing system, comprising:

a central processing unit (CPU) which includes an execution unit and a associated register file, the execution unit to process instructions of a plurality of instructions sets including a register-based instruction set and a stack-based instruction set;

a mechanism to maintain an operand stack for the stack-based instruction set in the register file with at least one of an underflow and overflow mechanism, wherein the processing system has a first state in which the CPU processes instructions using the register-based instruction set without a virtual machine, a second state in which the CPU processes instructions using the register-based instruction set within the virtual machine, and a third state in which the CPU processes instructions using the stack-based instruction set within the virtual machine, the processing system being configured to perform a method, comprising:

switching to the first state due to a reset command while in the third state or after power-on;

thereafter switching to the second state;

processing instructions while in the second state; and

switching to the third state.

88. The processing system of claim 87, wherein upon encountering an exception while in the third state, switching to the second state for further processing.

89. The processing system of claim 88, wherein upon encountering an exception while in the third state, the processing system switches to the second state for further processing of the exception.

90. The processing system of claim 88, wherein due to an exception while in the second state, the processing system switches from the second state to the first state.

91. The processing system of claim 88, wherein the processing system switches to the third state while in the virtual machine to execute the stack-based instruction set.

92. The processing system of claim 88 or claim 91, wherein an exception is generated for selected stack-based instructions.

93. The processing system of claim 91, wherein the stack-based instructions are virtual machine bytecodes.

94. The central processing unit of claim 74, claim 86, or claim 88, wherein the stack-based instruction generating an exception is selected from the group consisting of tableswitch, lookupswitch, getstatic, putstatic, getfield, putfield, invokevirtual, invokespecial, invokestatic, invokeinterface, new, newarray, arraylength, athrow, checkcast, instanceof, monitorenter, monitorexit, breakpoint, anewarray, imdep1, and imdep2.

95. The processing system of claim 87, wherein the processing is done using register-based instructions for the first and second states.

96. The processing system of claim 95, wherein the processing system switches to the third state while in the virtual machine.

97. The processing system of claim 87, wherein an error while in the third state switches the processing system to the second state.

98. The processing system unit of claim 87, further comprising for the instructions of the stack-based instruction set, processing said instructions in a hardware accelerator to process instructions of the stack-back instruction set prior to the processing of said instructions in the execution unit.

99. The processing system unit of claim 98, further comprising for the instructions of the stack-based instruction set, processing said instructions in a hard accelerator to process instructions of the stack-back instruction set prior to the processing of said instructions in the execution unit.

* * * * *

EXHIBIT 2

US007225436B1

(12) **United States Patent**
Patel

(10) **Patent No.: US 7,225,436 B1**
(45) **Date of Patent: *May 29, 2007**

(54) **JAVA HARDWARE ACCELERATOR USING MICROCODE ENGINE**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 315 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **09/687,777**

(22) Filed: **Oct. 13, 2000**

Related U.S. Application Data

(63) Continuation-in-part of application No. 09/208,741, filed on Dec. 8, 1998, now Pat. No. 6,332,215.
(60) Provisional application No. 60/239,298, filed on Oct. 10, 2000.

(51) **Int. Cl.**
G06F 9/45 (2006.01)
G06F 9/44 (2006.01)
G06F 15/00

(52) **U.S. Cl.** **717/139**; 717/118; 717/148; 712/41

(58) **Field of Classification Search** 717/136–140, 717/118, 148, 131, 143, 116, 134–137, 139, 717/165, 190; 712/137, 202, 203, 210, 36, 712/229; 711/108, 1, 103
See application file for complete search history.

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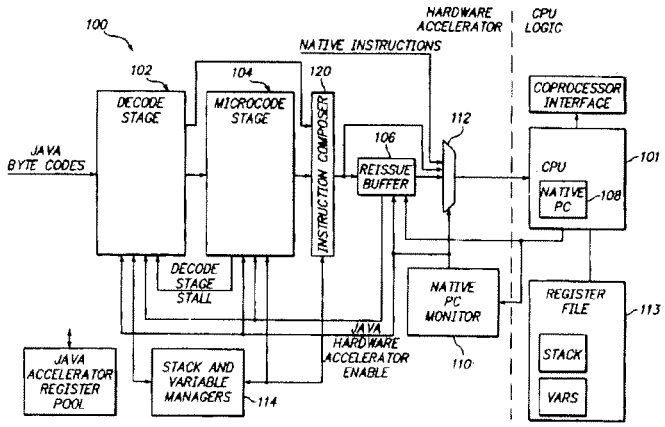
(57) **ABSTRACT**

A hardware Java™ accelerator is comprised of a decode stage and a microcode stage. Separating into the decode and microcode stage allows the decode stage to implement instruction level parallelism while the microcode stage allows the conversion of a single Java™ bytecode into multiple native instructions. A reissue buffer is provided which stores the converted instructions and reissues them when the system returns from an interrupt. In this manner, the hardware accelerator need not be flushed upon an interrupt A native PC monitor is also used. While the native PC is within a specific range, the hardware accelerator is enabled to convert the Java™ bytecodes into native instructions. When the native PC is outside the range, the hardware accelerator is disabled and the CPU operates on native instructions obtained from the memory.

22 Claims, 19 Drawing Sheets



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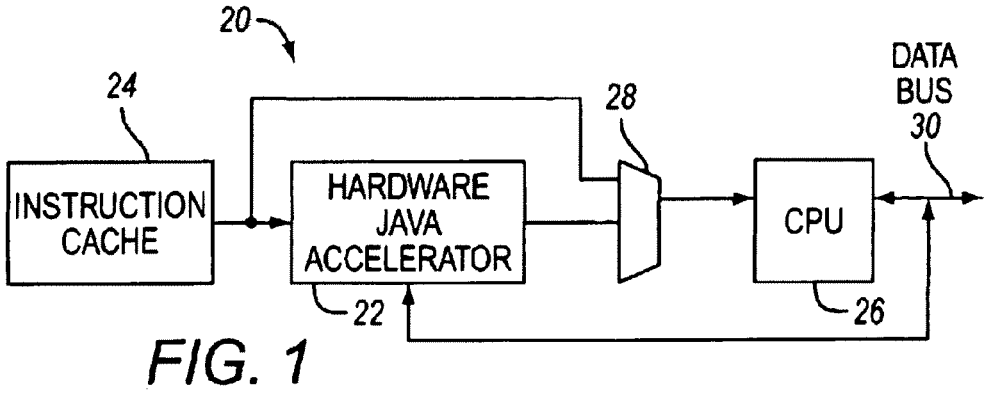
20
24
28
DATA BUS
30
INSTRUCTION CACHE
HARDWARE JAVA ACCELERATOR
CPU
22
26

FIG. 1

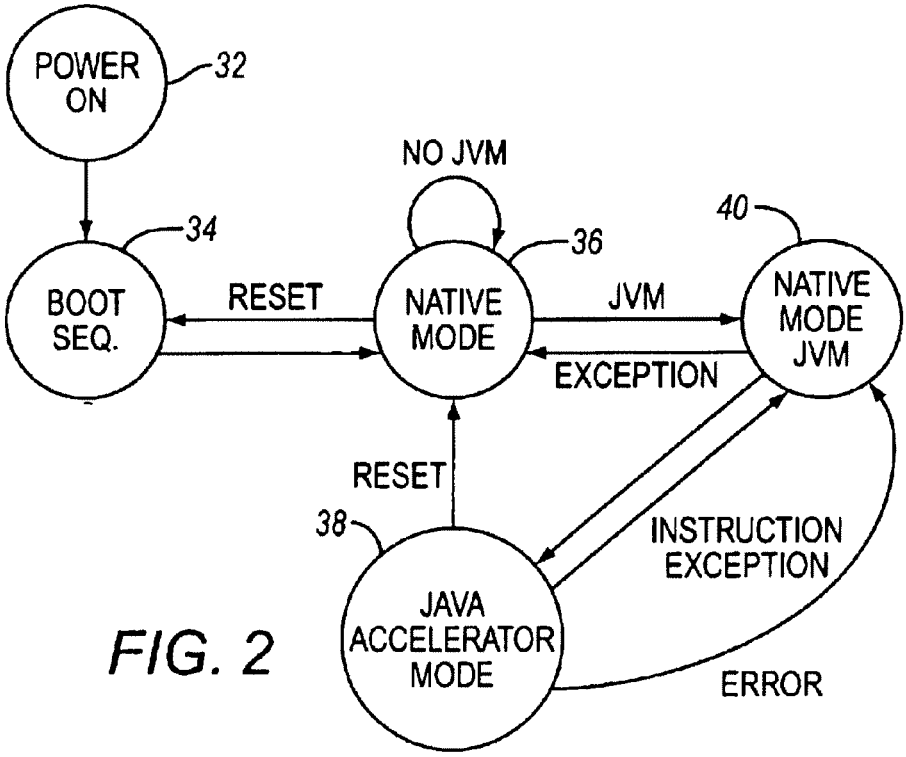
POWER ON
32
NO JVM
34
36
40
BOOT SEQ.
RESET
NATIVE MODE
JVM
NATIVE MODE JVM
EXCEPTION
RESET
38
INSTRUCTION EXCEPTION
JAVA ACCELERATOR MODE
ERROR

FIG. 2

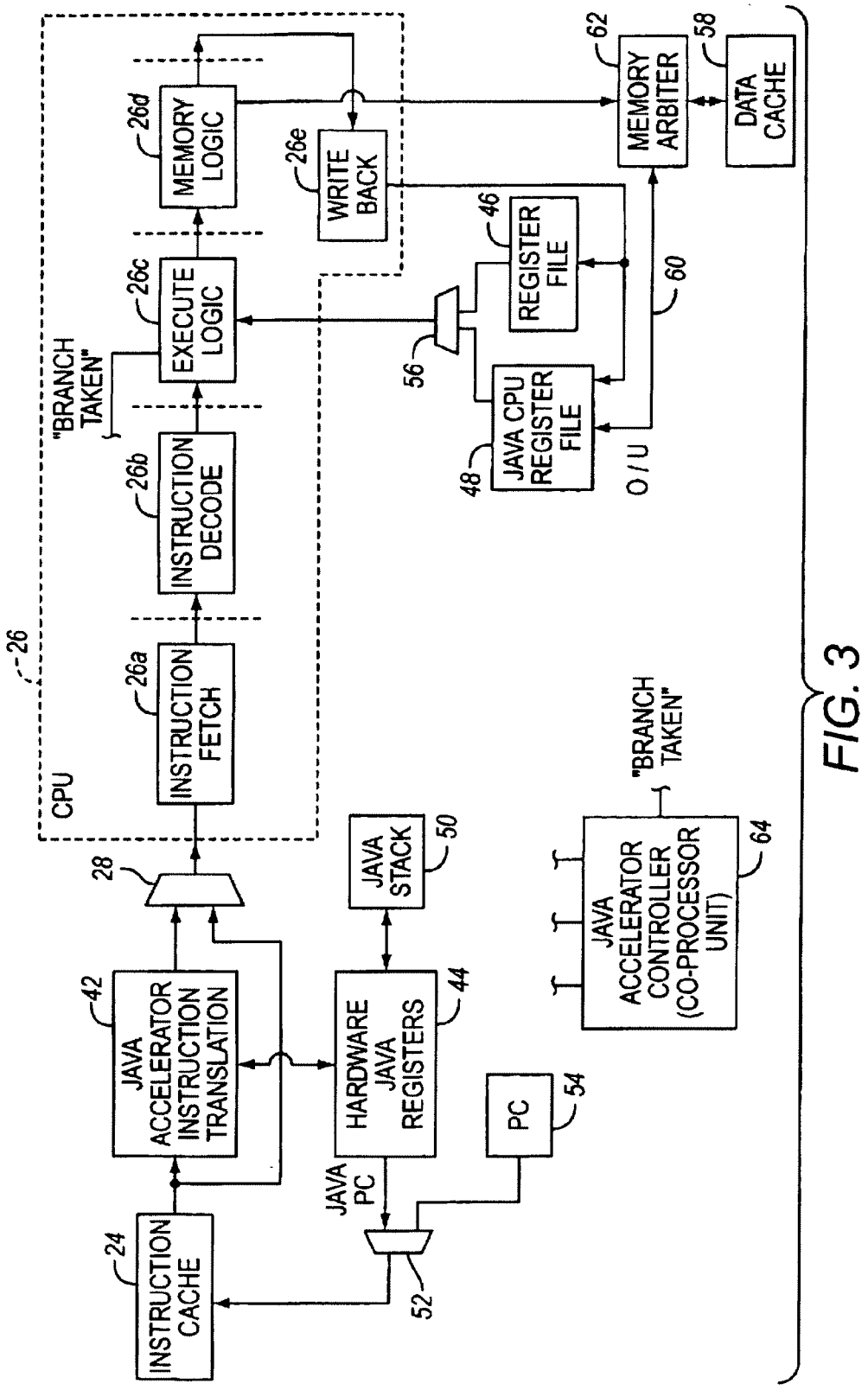
CPU
26
INSTRUCTION FETCH
26a
INSTRUCTION DECODE
26b
"BRANCH TAKEN"
EXECUTE LOGIC
26c
MEMORY LOGIC
26d
WRITE BACK
26e
28
JAVA ACCELERATOR INSTRUCTION TRANSLATION
42
INSTRUCTION CACHE
24
JAVA STACK
50
HARDWARE JAVA REGISTERS
44
JAVA PC
52
PC
54
REGISTER FILE
46
56
JAVA CPU REGISTER FILE
48
O / U
60
MEMORY ARBITER
62
DATA CACHE
58
"BRANCH TAKEN"
JAVA ACCELERATOR CONTROLLER (CO-PROCESSOR UNIT)
64

FIG. 3

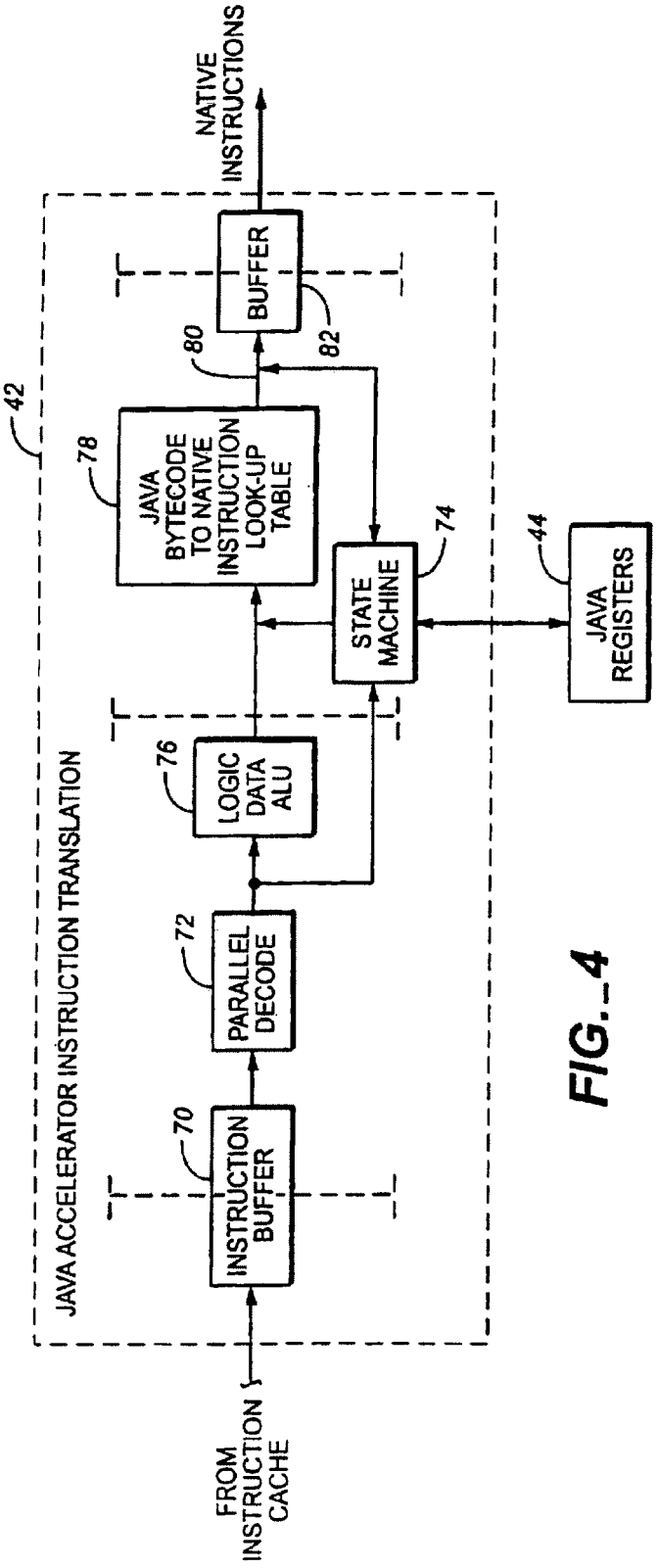
NATIVE INSTRUCTIONS
BUFFER
82
80
42
78
JAVA BYTECODE TO NATIVE INSTRUCTION LOOK-UP TABLE
74
STATE MACHINE
44
JAVA REGISTERS
76
LOGIC DATA ALU
72
PARALLEL DECODE
70
INSTRUCTION BUFFER
JAVA ACCELERATOR INSTRUCTION TRANSLATION
FROM INSTRUCTION CACHE

FIG._4

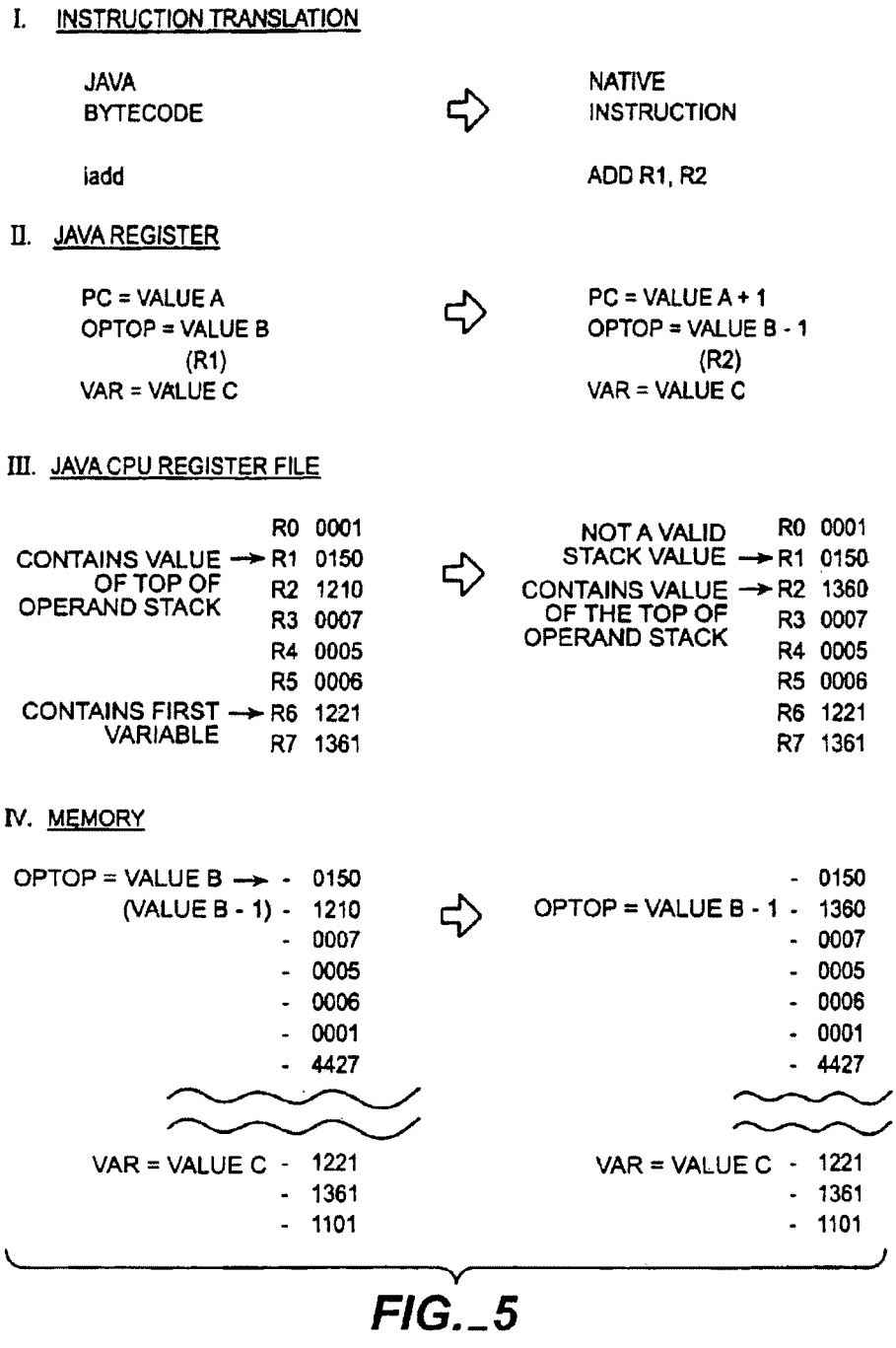
I. INSTRUCTION TRANSLATION
JAVA BYTECODE
NATIVE INSTRUCTION
iadd
ADD R1, R2
II. JAVA REGISTER
PC = VALUE A
OPTOP = VALUE B
(R1)
VAR = VALUE C
PC = VALUE A + 1
OPTOP = VALUE B - 1
(R2)
VAR = VALUE C
III. JAVA CPU REGISTER FILE
CONTAINS VALUE OF TOP OF OPERAND STACK
CONTAINS FIRST VARIABLE
R0 0001
R1 0150
R2 1210
R3 0007
R4 0005
R5 0006
R6 1221
R7 1361
NOT A VALID STACK VALUE
CONTAINS VALUE OF THE TOP OF OPERAND STACK
R0 0001
R1 0150
R2 1360
R3 0007
R4 0005
R5 0006
R6 1221
R7 1361
IV. MEMORY
OPTOP = VALUE B
(VALUE B - 1)
VAR = VALUE C
- 0150
- 1210
- 0007
- 0005
- 0006
- 0001
- 4427
- 1221
- 1361
- 1101
OPTOP = VALUE B - 1
- 0150
- 1360
- 0007
- 0005
- 0006
- 0001
- 4427
- 1221
- 1361
- 1101

FIG._5

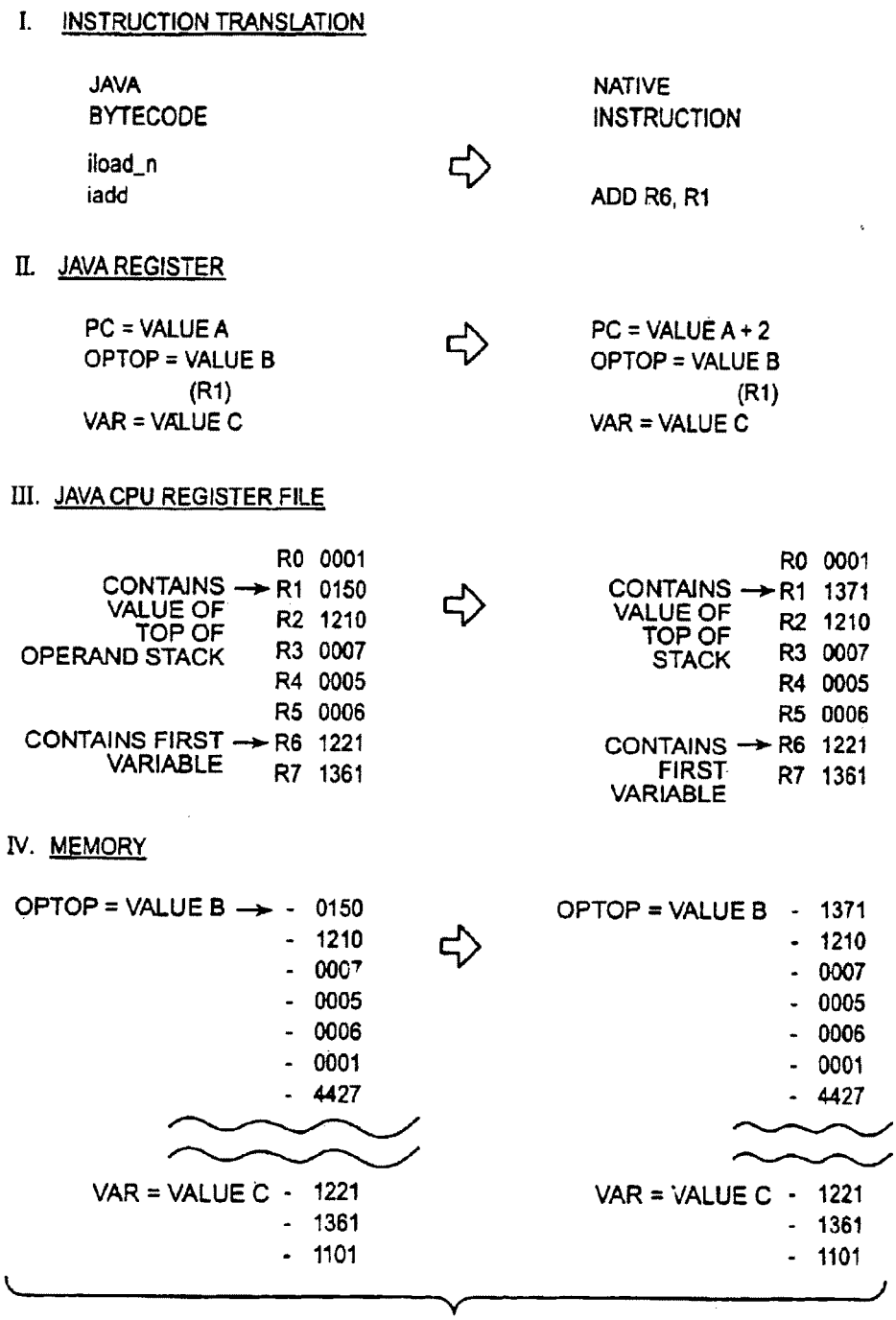
I. INSTRUCTION TRANSLATION
JAVA BYTECODE
iload_n
iadd
NATIVE INSTRUCTION
ADD R6, R1
II. JAVA REGISTER
PC = VALUE A
OPTOP = VALUE B (R1)
VAR = VALUE C
PC = VALUE A + 2
OPTOP = VALUE B (R1)
VAR = VALUE C
III. JAVA CPU REGISTER FILE
CONTAINS VALUE OF TOP OF OPERAND STACK
CONTAINS FIRST VARIABLE
R0 0001
R1 0150
R2 1210
R3 0007
R4 0005
R5 0006
R6 1221
R7 1361
CONTAINS VALUE OF TOP OF STACK
CONTAINS FIRST VARIABLE
R0 0001
R1 1371
R2 1210
R3 0007
R4 0005
R5 0006
R6 1221
R7 1361
IV. MEMORY
OPTOP = VALUE B
- 0150
- 1210
- 0007
- 0005
- 0006
- 0001
- 4427
VAR = VALUE C
- 1221
- 1361
- 1101
OPTOP = VALUE B
- 1371
- 1210
- 0007
- 0005
- 0006
- 0001
- 4427
VAR = VALUE C
- 1221
- 1361
- 1101

FIG._6

Opcodes Mnemonic	Opcode xHH	Excep Gen
nop	0x00	
aconst_null	x01	
iconst_m1	x02	
iconst_n(0-5)	x03 - x08	
lconst_n(0-1)	x09 - x0a	
fconst_n(0-2)	x0c - x0d	
dconst_n(0-1)	x0e -x0f	
bipush	x10	
sipush	x11	
ldc	x12	y
ldc_w	x13	y
ldc2_w	x14	y
iload	x15	
lload	x16	
fload	x17	
dload	x18	
aload	x19	
iload_n(0-3)	x1a - x1d	
lload_n(0-3)	x1e - x21	
fload_n(0-3)	x22 - x25	
dload_n(0-3)	x26 - x29	
aload_n(0-3)	x2a - x2d	
iaload	x2e	
laload	x2f	
faload	x30	
daload	x31	
aaload	x32	
baload	x33	
caload	x34	
saload	x35	
istore	x36	
lstore	x37	
fstore	x38	
dstroe	x39	
astroe	x3a	
istore_n(0-3)	x3b - x3e	
lstore_n(0-3)	x3f - x42	
fstore_n(0-3)	x43 - x46	
dstore_n(0-3)	x47 - x4a	
astore_n(0-3)	x4b - x4e	
iastore	x4f	
lastore	x50	
fastroe	x51	
dastore	x52	
bastore	x53	
aastore	x54	
castroe	x55	
sastore	x56	

FIG._7A

pop	x57	
pop2	x58	
dup	x59	
dup_x1	x5a	
dup_x2	x5b	
dup2	x5c	
dup2_x1	x5d	
dup2_x2	x5e	
swap	x5f	
iadd	x60	
ladd	x61	
fadd	x62	y
dadd	x63	y
isub	x64	
lsub	x65	
fsub	x66	y
dsub	x67	y
imul	x68	
lmul	x69	
fmul	x6a	y
dmul	x6b	y
idiv	x6c	y
ldiv	x6d	y
fdiv	x6e	y
ddiv	x6f	y
irem	x70	y
lrem	x71	y
frem	x72	y
drem	x73	y
ineg	x74	
lneg	x75	
fneg	x76	y
dneg	x77	y
ishl	x78	
lshl	x79	
ishr	x7a	
lshr	x7b	
iushr	x7c	
lushr	x7d	
iand	x7e	
land	x7f	
ior	x80	
lor	x81	
ixor	x82	
lxor	x83	
iinc	x84	
i2l	x85	y
i2f	x86	y
i2d	x87	y
l2i	x88	y
l2f	x89	y
l2d	x8a	y

FIG._7B

f2l	x8b	y
f2l	x8c	y
f2d	x8d	y
d2i	x8e	y
d2l	x8f	y
d2f	x90	y
i2b	x91	
i2c	x92	
i2s	x93	
lcmp	x94	y
fcmpl	x95	y
fcmpg	x96	y
dcmpl	x97	y
dcmpg	x98	y
ifeq	x99	
ifne	x9a	
iflt	x9b	
ifge	x9c	
ifgt	x9d	
ifle	x9e	
if_icmpeq	x9f	
if_icmpne	xa0	
if_icmplt	xa1	
if_acmpge	xa2	
if_cmpgt	xa3	
if_icmple	xa4	
if_acmpeq	xa5	
if_acmpne	xa6	
goto	xa7	
jsr	xa8	
ret	xa9	
tableswitch	xaa	y
lookupswitch	xab	y
ireturn	xac	
lreturn	xad	
freturn	xae	
dreturn	xaf	
areturn	xb0	
return	xb1	
getstatic	xb2	y
putstatic	xb3	y
getfield	xb4	y
putfield	xb5	y
invokevirtual	xb6	y
invokespecial	xb7	y
invokestatic	xb8	y
invokeinterface	xb9	y
xxunsedxxx	xba	y
new	xbb	y
newarray	xbc	y
anewarray	xbd	y
arraylength	xbe	y

FIG._7C

athrow	xbf	y
checkcast	xc0	y
instanceof	xc1	y
monitorenter	xc2	y
monitorexit	xc3	y
wide	xc4	y
multianewarray	xc5	y
ifnull	xc6	y
ifnonnull	xc7	y
goto_w	xc8	
jsr_w	xc9	
ldc_quick	xcb	y
ldc_w_quick	xcc	y
ldc2_w_quick	xcd	y
getfield_quick	xce	y
putfield_quick	xcf	y
getfield2_quick	xd0	y
putfield2_quick	xd1	y
getstatic_quick	xd2	y
putstatic_quick	xd3	y
gtestatic2_quick	xd4	y
putstatic2_quick	xd5	y
invokevirtual_quick	xd6	y
invokenonvirtual_quick	xd7	y
invokesuper_quick	xd8	y
invokestatic_quick	xd9	y
invokeinterface_quick	xda	y
invokevirtualobject_quick	xdb	y
new_quick	xdc	y
anewarray_quick	xde	y
multinewarray_quick	xdf	y
checkcast_quick	xe0	y
instanceof_quick	xe1	y
invokevirtual_quick_w	xe2	y
getfield_quick_w	xe3	y
putfield_quick_w	xe4	y
breakpoint	xca	y
impdep1	xfe	y
impdep2	xff	y

FIG._7D

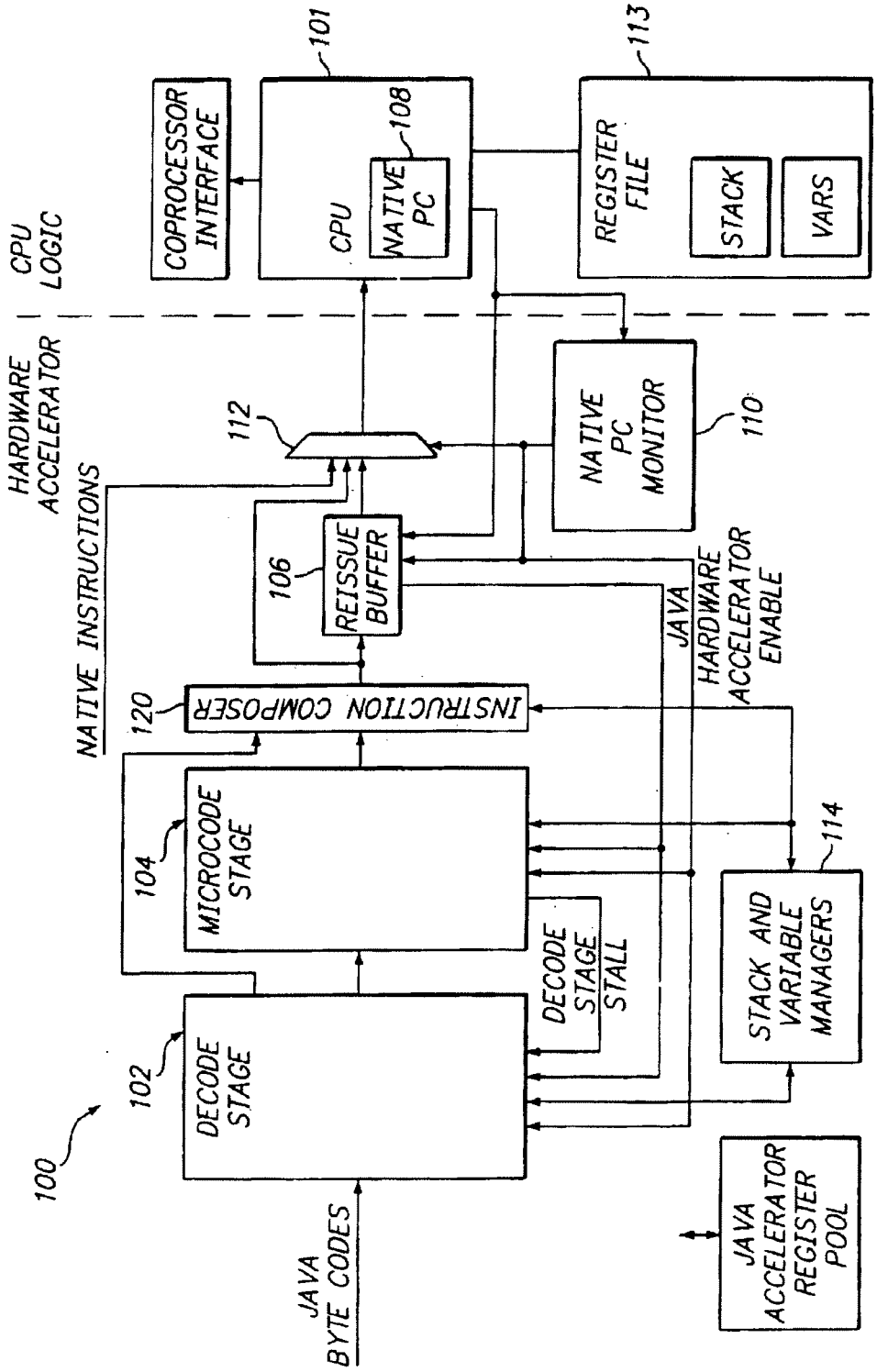
CPU LOGIC
HARDWARE ACCELERATOR
NATIVE INSTRUCTIONS
JAVA BYTE CODES
100
101
102
104
106
108
110
112
113
114
120
COPROCESSOR INTERFACE
CPU
NATIVE PC
REGISTER FILE
STACK
VARS
NATIVE PC MONITOR
REISSUE BUFFER
INSTRUCTION COMPOSER
MICROCODE STAGE
DECODE STAGE
DECODE STAGE STALL
JAVA HARDWARE ACCELERATOR ENABLE
STACK AND VARIABLE MANAGERS
JAVA ACCELERATOR REGISTER POOL

FIG. 8